DOE

ENERGY STORAGE

SYSTEMS PROGRAM

# Quarterly Progress Report
# for
# October — December 2003

# (First Quarter / Fiscal Year 2004)

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**Energy Storage Systems Department**

**(ESS)**

**Sandia National Laboratories, Albuquerque, NM**

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# SYSTEM INTEGRATION

## ***Integration and Testing of Energy Storage with Flexible AC Transmission System Devices***

*SNL Contact:* Stan Atcitty
*Contractor:* University of Missouri-Rolla

**Project Overview**

Initiated in April 1998, the purpose of this work is to investigate the feasibility of interfacing a BESS (Battery Energy Storage System) into bulk power systems through an interface with FACTS devices.

Over the next two years, several prototype FACTS/BESS devices were designed, built, and tested. 2001 and 2002 focused on designing power electronics topologies to best exploit the active power capabilities of BESS. Several multi-level converters were identified, designed and built. Additional theoretical analyses developed comparison metrics to determine the impact of the various FACTS/BESS devices on bulk power system stability.

This work provided clear experimental and theoretical support that adding energy storage capabilities to existing FACTS devices provides superior performance and control.

There are several compelling reasons to consider a multilevel converter topology for the StatCom/BESS. Well-known reasons include lower harmonic injection into the power system, decreased stress on the electronic components due to decreased voltages, and lower switching losses. Various multilevel converters also readily lend themselves to a variety of Pulse Width Modulation (PWM) strategies to improve efficiency and control. The use of multilevel converters can readily reduce the size of the individual energy storage units without compromising performance.

One additional advantage of incorporating energy storage and the StatCom is that the converter DC link capacitor can be significantly decreased, because only a small capacitor is required to smooth the DC current seen by the battery.

In 2003, two multilevel converters, the cascaded and the diode-clamped converters, were compared and contrasted to ascertain the advantages and disadvantages of each topology for the StatCom/BESS. The fourth quarter of 2003 concentrated on comparing battery configurations for the diode-clamped StatCom/BESS and experimental verification of the cascaded StatCom/BESS. Those procedures revealed an attractive feature of the diode-clamped topology: the number of battery sets can be reduced from four to two by placing several connections across only half of the DC link capacitors.

After comparison testing of oscillation dampening between the two-set and four-set battery system configurations, an assertion could be supported that a multi-level diode-clamped StatCom/BESS with only two battery sets can achieve nearly the same transient stability support as the same topology StatCom./BESS with four battery sets, leading to significant cost savings.

The diode-clamped multilevel converter resulted in a novel configuration which enabled a much smaller battery system to be utilized without significantly impacting the dynamic control capabilities of the StatCom/BESS.

**First Quarter Status**

The only activity in this quarter was the preparation and presentation of the paper: *Efficient Utilization of Battery Energy Storage in a Multilevel Converter StatCom* , to be presented at EESAT 2003 in October 2003.

FY04 funding is pending approval by DOE.

## ***NMSU Capstone[1] Design Project – Apparatus For Testing Charge/Discharge Characterisitics Of Supercapacitors***

*SNL Contact:* Stan Atcitty
*Contractor:* New Mexico State University, Las Cruces, NM — (Satish J. Ranade)

**Project Overview**

The purpose of this education-related project is to introduce engineering students to electric energy storage and related technology, by offering a Design Project class at New Mexico State University (NMSU). The design project requirements are developed in areas of interest to the DOE ESS program.

This project provides significant visibility for the energy storage area and DOE programs amongst the undergraduate and graduate student body at NMSU. It introduces a group of students to this important area and trains them in the technologies that they will use in their careers. As such, the project is important to DOE's mission in developing and disseminating technology. It is anticipated that similar classes involving electric energy storage will be offered in the future.

The Klipsch School of Electrical and Computer Engineering at NMSU requires all BSEE students to complete a six-credit design class. Students with senior standing must design a reasonably complex system, drawing upon several specialties such as power, electronics, computers, control, etc. The class also provides significant experience in interdisciplinary teamwork, written and oral communication, and leadership. The Accreditation Board for Engineering and Technology calls such classes "Capstones", since this is the final class that students take.

[1] Here "Capstone" refers to the final class taken by students and not to a commercial brand of microturbine!

DOE has an interest in the use of electrochemical and double-layered capacitors (so-called ‘super-capacitors’, or ‘ultra-capacitors’), as energy storage media in power system applications. Therefore, in the first Design Project, offered in FY02, students successfully designed and fabricated a “Super-capacitor Test System.” SNL served as the ‘customer’ and students made a midterm and final presentation to SNL personnel.

The class was offered again in FY03. A class proposal was submitted and approved by Klipsch School. The system requirements for the design are as follows.

- Power electronics suitable for charging and discharging super-capacitors according to a specified protocol;
- A user interface based on National Instruments hardware and Labview software; the interface will allow user to select and run test protocols; collect and display voltage, current, power and energy waveforms; calculate and display performance metrics; and
- Necessary software to implement specific protocols such as constant power discharge.

Deliverables consist of the test system hardware and software, user’s manuals, and a demonstration.

While the FY02 project focused on a prototype system, the project begun in the latter part of FY03 is directed towards a usable product. As such, students must carefully consider protection and safety requirements, as well as packaging.

A team of four students commenced work on the project in August 2003. The project constitutes their 6-credit capstone class. Based on specifications given the team has outlined the hardware and software requirements for the project. The team has developed work assignments, a management approach, and a set of milestones. Milestones were reviewed on a regular basis.

The project team made a formal technical presentation to Mr. John Boyes and Mr. Stan Atcitty of SNL who serve the in role of “Customers” on behalf of the DOE. This activity is a required part of design projects.

**First Quarter Activities**

The team completed the design and fabrication of hardware, shown in Figure 1:

- A three-phase rectifier;
- A dc-dc buck converter, fed from the rectifier, to provide coarse control of charging voltage based on actual capacitor voltage; and
- A dc-dc Sepic converter, fed from the buck, which operates under closed loop control, to maintain a constant charging current into the capacitor.

Using National Instruments’ Labview ® program, the team also designed software to control the dc-dc converters. As shown in Figure 2, the user interface allows one to enter a desired voltage and charging current. Slide bar displays show the capacitor voltage and current as the capacitor charges. The controller samples capacitor and dc-dc converter voltages and currents and provides set-points for the coarse buck converter and the Sepic current controller.

The team was able to demonstrate the basic capabilities of the system. However, the goal of allowing the user to program arbitrary charging protocols was not met. Although, learning outcomes related to design, problem solving, and project budgeting and management were met.

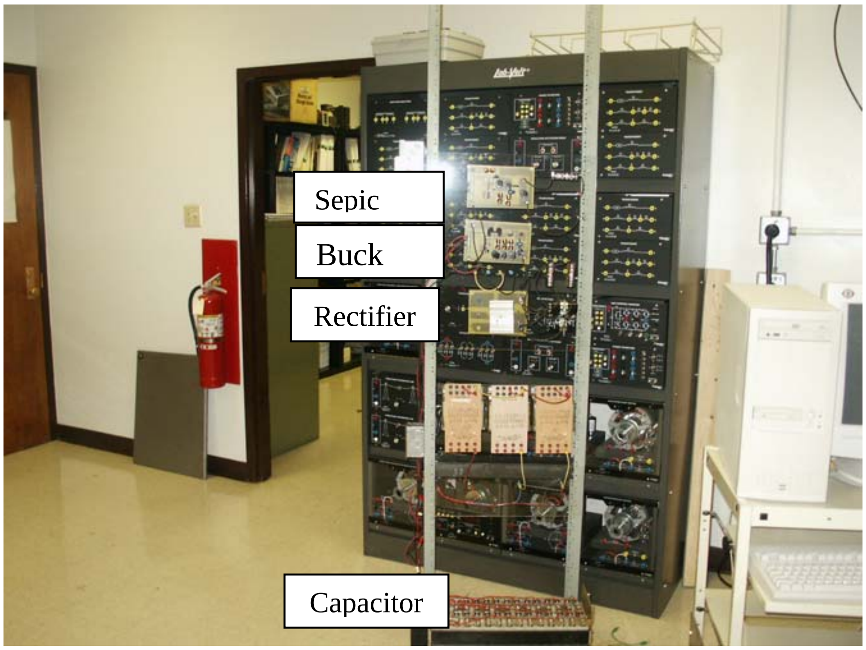



**Figure 1: Charger Hardware**

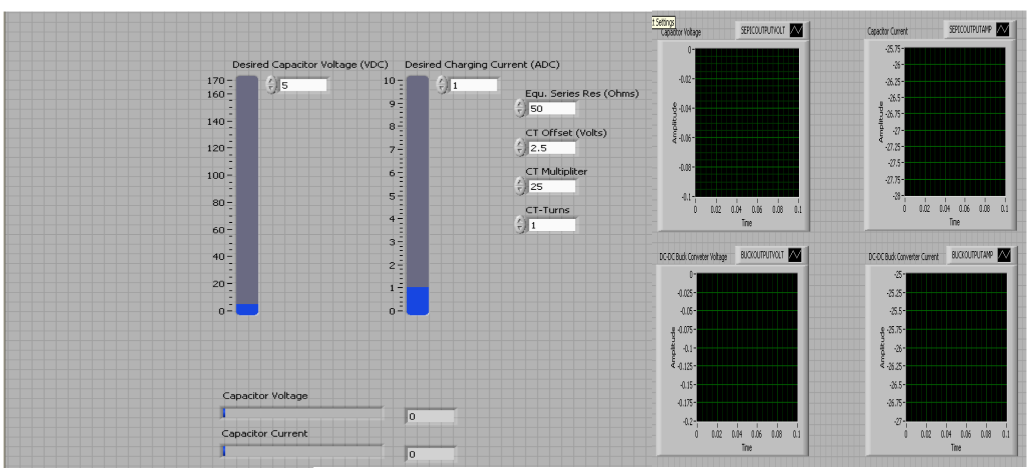



**Figure 2: Software User Interface**

## ***Hardware Prototype of Device to Improve Transient Load Ability of Distributed Energy Resources***

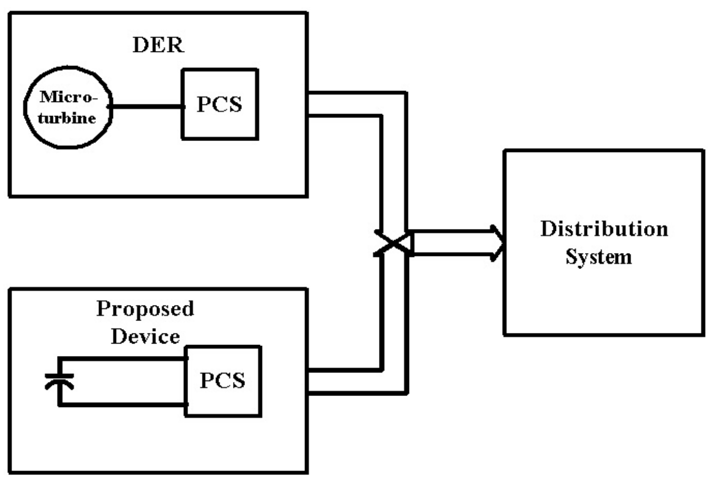
*SNL Contact:* Stan Atcitty
*Contractor:* New Mexico State University, Las Cruces, NM — Dr. Satish J. Ranade

**Project Overview**

The purpose of this project is to develop a prototype for an energy storage-based device to improve transient load performance of Distributed Energy Resources (DER). Such a device could help stabilize the operations of an isolated DER grid undergoing a transient load.

DER often cannot operate when isolated from a utility because the inverter at the interface is unable to handle large transient loads, such as motor starts. The prototype device would use an electrochemical capacitor to supply energy during short periods of such transient loads.

As shown in the schematic in Figure 1, an electro-chemical capacitor, or other storage source, is interfaced to the DER terminals using a simple, short-term rated, dc-ac inverter. The feasibility of the concept depends on the cost and performance of energy storage elements and optimized design of the inverter. A conceptual design was developed using simulation studies, and an invention disclosure was filed at SNL.




A single-phase prototype was fabricated and demonstrated in the first year of the project, FY02. That prototype used an electrochemical capacitor to supply energy during short periods of transient loads. At the onset of a large transient load, the capacitor supplied the excess current needed. As a result, the DER could 'ride out' the disturbance.

The feasibility of the entire concept depends on the cost and performance of energy storage elements and optimized design of the inverter. Therefore, the work in FY03 focused on developing a three-phase prototype, which resulted in an optimum design of a device that will permit comprehensive evaluation of potential benefits. Additional efforts included examination and documentation of the performance of several commercial capacitor technologies as energy storage elements. The design was completed in the first two quarters, and two prototypes were fabricated and successfully tested with several capacitor technologies during the third and fourth quarters.

**First Quarter Status:**

FY04 first quarter activities focused on developing a final report in the form of two MSEE technical reports. Graduate student Xin Jiang's report [1] focuses on design aspects of the hardware prototype and test results. Laxmi Terala's technical report [2] focuses on the behavior of the super capacitors used for energy storage. Both reports have been provided to SNL. Comparative results were also presented at the 2003 EESAT (Electrical Energy Storage – Applications & Technology) conference.

The device readouts in Figure 2 illustrate the three-phase prototype's operation with an ESMA capacitor, prior to and during a motor start load.

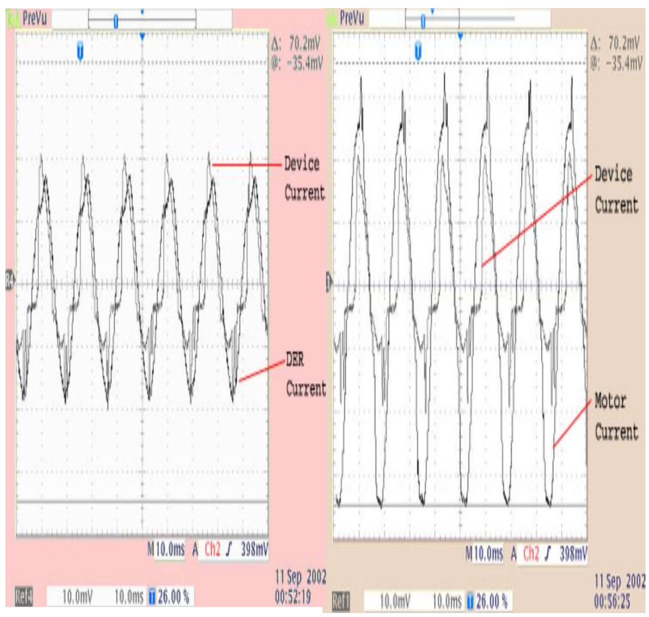



**Figure 2: 3-Phase prototype device operation with ESMA Electrochemical capacitor. DER current and prototype current (left); motor starting current and prototype current (right).**

The primary goal of the project has been accomplished and will provide necessary documentation for SNL's effort to possibly obtain a patent. It is recommended that the possibility of commercialization be explored.

[1] Xin Jiang, "Transient PCS Solution With Optimized Thermal Design for DER System", MSEE Technical report, Electric Utility Management Program, New Mexico State University, December 2003
[2] Laxmi Deepa Terala, "Applications of Energy Storage Capacitors in Power Systems ", MSEE Technical report, Electric Utility Management Program, New Mexico State University, December 2003.

## ***RAPS Testing Methods***

*SNL Contact:* Paul Butler
*Contractor:* Energetics, Inc. — Ed Skolnik

**Project Overview**

The DOE ESS Program at Sandia has coordinated with the International Lead Zinc Research Organization (ILZRO) on a project to define standard test-cycle regimes for remote area power supply (RAPS) systems. In FY99, a major decision was made to integrate this project with the existing infrastructure of the Institute of Electrical and Electronics Engineers (IEEE) Standards Coordinating Committee (SCC) 21, Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage. The documents in process in the Energy Storage Subsystems Working Group (ESSWG) of SCC 21 all relate to distributed energy resource energy systems with battery storage used in a stand-alone mode (no utility connection).

Sandia, ILZRO, and Energetics Inc., a contractor to SNL on this project, have coordinated the activities of the ESSWG and have assisted in preparing new guidelines for RAPS systems — those that use a renewable generation resource, energy storage, and a fossil-fueled generator in a stand-alone mode. Work is in progress by the ESSWG on three Project Action Requests (PARs) and on the review of two existing standards:

PAR 1361 – Guide for Selection, Charging, Test and Evaluation of Lead-Acid Batteries Used in Stand-Alone Photovoltaic Systems (Status: Approved)

PAR 1561 – Draft Guide for Optimizing the Performance and Life of Lead-Acid Batteries in Hybrid Remote Area Power Supply Systems (formerly Guide for Sizing Stand-Alone Energy Systems) (Draft 7)

PAR 1562 – Draft Guide for Array and Battery Sizing in Stand-Alone Photovoltaic (PV) Systems (Draft 1)

Standard 1013-2000 – Recommended Practice for Sizing Lead-Acid Batteries for Photovoltaic (PV) Systems

Standard 937-2000 – Recommended Practice for Installation and Maintenance of Lead – Acid Batteries for Photovoltaic (PV) Systems

### First Quarter Status

The ESSWG conducted no meetings in the first quarter of FY04. Meetings are being scheduled for 2004.
However, the DOE/ESS Program budget for FY04 has yet to be resolved. Until it is, only modest work will be performed on this project.

## ***Peru System Monitoring***

*SNL Contact:* Paul Butler
*Contractor:* International Lead Zinc Research Organization (ILZRO) — Jerry Cole

### Project Overview

In July 1997, the International Lead-Zinc Research Organization (ILZRO), the U.S. Solar Energy Industries Association (SEIA), and the Ministry of Energy and Mines of the government of Peru signed a Memorandum Of Understanding (MOU) for a collaborative project to design, install, and operate advanced, remote area power supply (RAPS) systems that include lead-acid batteries in isolated, in off-grid locations. Two Peruvian sites were selected with the goal of producing battery/photovoltaic systems capable of 30 kWp and 60 kWp, respectively.

The goal of this pilot project is to demonstrate that battery-based hybrid power systems are technically and financially viable options for rural, off-grid electrification. This goal applies to not only the technical aspects of the equipment, but also to the social and economic development needs of the rural, remote communities.

The first phase of the project was a feasibility study for photovoltaics in combination with storage, power electronics, and controls for use in remote villages along the Amazon River valley, including an estimation of the economic benefits. The MOU signatories and the ESS Program shared the cost of the study. An ILZRO report documents the results.

With funding provided by DOE/ESS and ILZRO (through the Peruvian government, the World Bank and other financial institutions), the project entered the hardware development and installation phase near the end of FY01 and continued throughout FY02. Orion Energy of Frederick, MD, is the system integrator for all the equipment and is developing the data acquisition system (DAS) with DOE/ESS support.

Two villages are to serve as prototype test sites: Padre Cocha with a 30-kWp electric system and Indiana with a 60-kWp system. Both villages are near Iquitos, which is approximately a one and one-half hour flight from Lima on the Pacific coast.

**First Quarter Status**
Most of the early start-up problems on the 30-kWp Padre Cocha system have been resolved; however, some of the electrical distribution and load issues remain a problem and are being addressed through a combination of reduction in the 24-hour cyclic operation and other measures.
When it was discovered that the load was higher than originally anticipated, a determination of the causes turned out to be a combination of factors, including a lack of switches in the street lighting, lack of switches in homes, use of inappropriate lighting fixtures, and clandestine connections.  All of these issues are being addressed by the local utility through:

- Energy efficiency training,
- Installation of appropriate switches,
- Elimination of clandestine connections, and
- Installation of meters.

Although some of these balance-of-system (unrelated to the battery) issues persist, the system has been operational since October 2003.

The government of Loreto, which is supplying funds for the PV panels, has indicated that they will provide funding for the PV panels for the village of Indiana (the 60-kWp RAPS) after three months of successful operation of the Padre Cocha installation.  All components for the Indiana installation, except for the PV panels, are currently in Iquitos (staging area for both installations). Therefore, installation of the second system can progress rather quickly once the PV panels are purchased.

## ***ABESS (Advanced Battery Energy Storage System)/PV System***

*SNL Contact:* Nancy Clark
*Contractor:* ZBB, Inc. — Robert Parry

**Project Overview**

This project has been providing the field testing for two advanced BESS (200-kW/400-kWh and 50-kW/100-kWh) based on zinc/bromine battery technology in load-leveling/peak shaving applications.

DOE/ESS has a long-term project to develop zinc/bromine batteries with ZBB, which has built a 200-kWh/400-kWh ABESS in cost-shared contracts with the ESS Program.  The first real-time test of the system was in 2000 at the Detroit Edison Akron site, which has power quality problems during the fall grain-drying process.  The test proved successful and the unit was returned to ZBB for refurbishing.

In August 2001, the system was moved to the Detroit Edison Lum site for summer load-leveling, where it ran successfully into the fall of 2001.  Following that initial testing, the system was decommissioned and returned to ZBB for refurbishing. The ABESS was sent back to the Lum site in the summer of 2002 and testing continued through the first quarter of FY03 (fall 2002).

Following that testing, four modules were returned to ZBB for refurbishing. The remaining four modules and the PCS remained at the Lum site for monitoring over the winter months. Original plans were to return the four remaining modules along with the shipping container and the power conversion equipment (PCS) to ZBB for reconditioning; but they remained at the Lum site while ZBB worked with Detroit Edison to find a site for another field demonstration. Essentially, this concluded testing of the 200-kWh/400-kWh ABESS.

The second part of the project provides field testing for a 50-kW/100-kWh advanced battery energy storage system (ABESS) based on zinc/bromine battery technology in load-leveling/peak shaving applications. PowerLight contracted with the Greenpoint Manufacturing and Design Center (GMDC), a non-profit arts and industry organization that purchases and rehabilitates historic buildings in the Greenpoint area of Brooklyn, to install a 50-kWac PV (photovoltaic) system at PowerLight's Humboldt Street facility. The 50 kWac PV system will be integrated with the ZBB 50-kW/100-kWh ABESS to absorb weekend PV production and dispatch it throughout the week to help reduce the customer load.

The 100-kWh ABESS comprises two identical cabinets (see Figure 1). Each cabinet includes a 50-kWh battery and a 25-kW/30-kVA power conversion system (PCS). Each cabinet is designed as a wye-connected, three-phase, 208-V, 60-Hz source or load. The battery is located inside the lower portion of the cabinet, while the PCS is contained in a separate compartment at the top of the cabinet (see Figure 2). The control equipment is located in a sealed box attached to the inside door of the battery compartment. The cabinet design allows separate access to either the battery or the PCS.


**Figure 1. 100-kWh ABESS.**

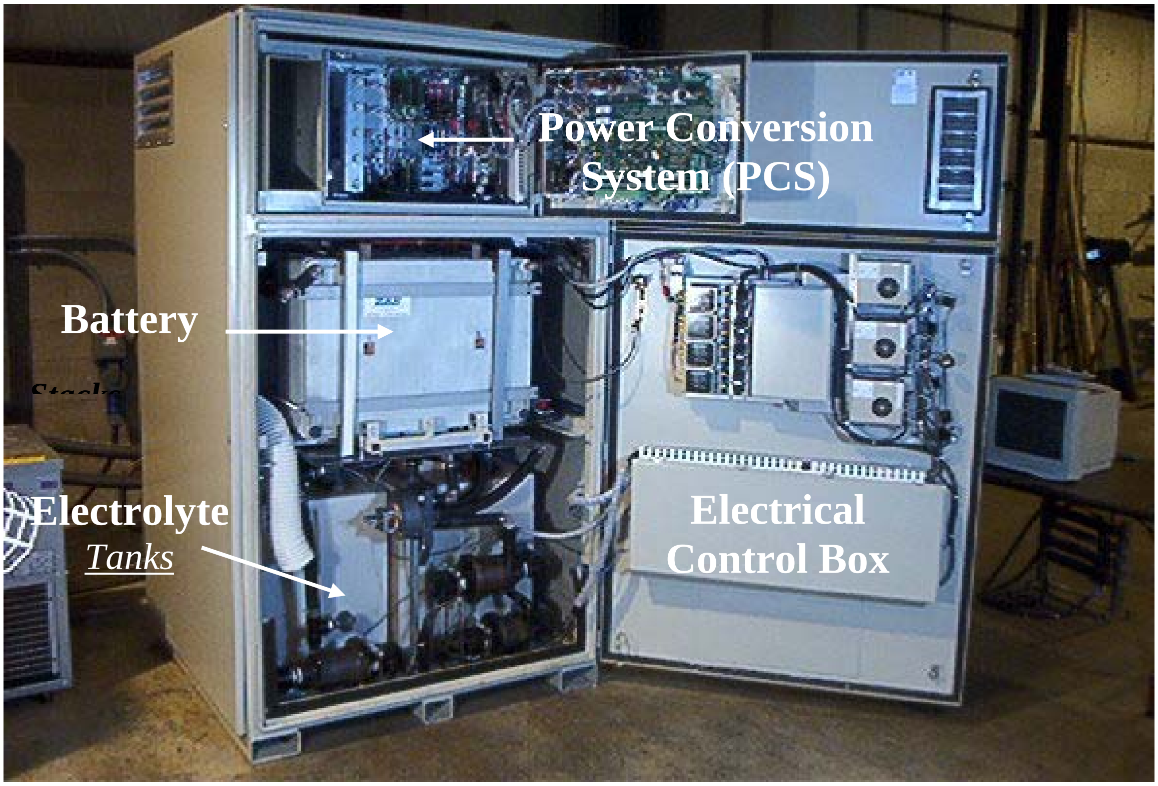



**Figure 2. System cabinet showing battery and PCS compartments.**

Factory testing of this system was successfully completed in FY03. The factory test procedures were designed to ensure that the system met all of the operational requirements and that it demonstrated a high level of reliability prior to shipment to the customer site. The system has demonstrated the ability to provide 108 kWh of energy at an efficiency of 75% (DC/DC) while cycling continuously for one week, with no manual intervention or shutdowns, and delivered 4 MWh of energy during the 3-month factory test period.

### First Quarter Status

Delivery and installation of the system at the demonstration site was delayed because the customer had not yet completed the electrical connections for the system nor installed the required safety fencing. Delivery and installation are expected next quarter.

## ***Li Ion BESS***

*SNL Contact:* Nancy Clark
*Contractor:* SAFT, Inc. — Salah Oweiss

**Project Overview**

This project is part of the ESS Program's advanced energy storage (AES) component development initiative, which has as its ultimate goal the development and testing of AES components large enough to be used in field demonstrations and to find industry partners to support these field demonstrations (including cost sharing). Specifically, the goal of this project is to design and construct a 100-kW/1 minute (1.67 kWh) Li-ion battery energy storage system for use in providing power quality for grid-connected microturbines.

In FY03, two electric utilities agreed to partner with the ESS Program in field demonstrations at their facilities. Consequently, two complete systems were designed and assembled. Factory acceptance testing was successfully completed on both systems and they were sent to the appropriate utility partners for field qualification. Initial results from both utility partners showed that the systems met, and in some cases exceeded, the specifications of the demonstrations.

The demonstration at Southern Company Services (SCS) used the BESS to supplement distributed generation (via microturbine) and to provide load-following capability. During the demonstration, the system was run at its rated power level of 100-kW for 3 minutes, which exceeded the battery design requirements by a factor of three. The system was available for approximately 1200 hours. Characterization testing is continuing at the SCS laboratory. When the characterization is complete, SCS hopes to find a customer site suitable for a field demonstration.

The demonstration at American Electric Power (AEP) used the BESS as a UPS. The system completed the demonstration successfully and was available for 1146 hours. AEP is further characterizing the battery, and based on the test results, they too hope to find a customer site for a field demonstration.

The work completed during this project should help to realize the advantages of Li-ion technology for applications where more traditional battery types (specifically lead-acid) are now used. Further, it is hoped that with wider use in larger applications, this technology can eventually compete with lead-acid batteries on a cost-per-life-cycle basis.

**First Quarter Status**

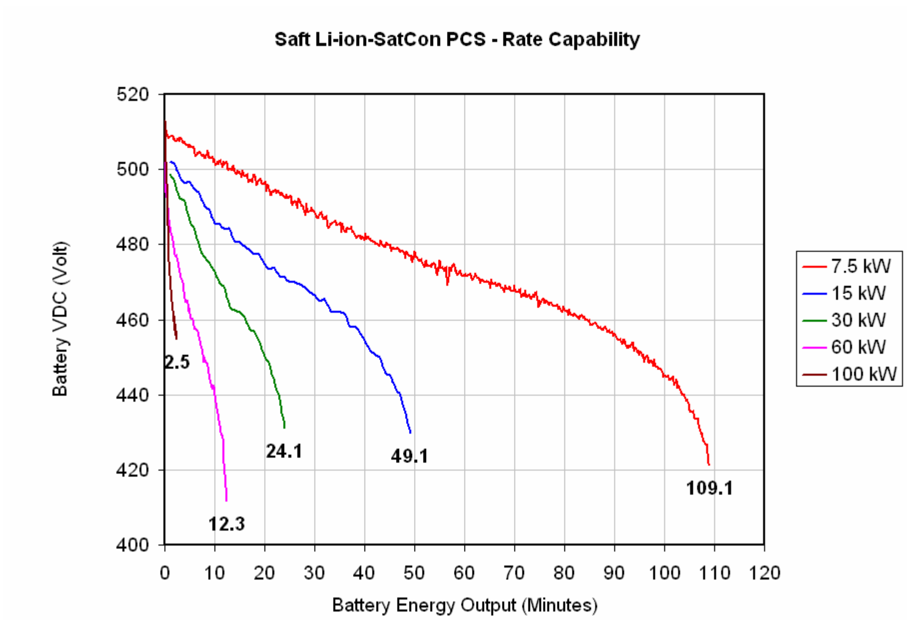
Testing at AEP was ongoing this quarter, without incident.

Characterization testing at the SCS laboratory was also ongoing during this quarter. Some problems were identified in the battery monitoring system (BMS), which was then returned to SAFT for further diagnostics and repair. The problems were corrected and the BMS module was returned to SCS and successfully re-installed in the BESS.

One of the battery modules experienced irregular voltage fluctuations during a test series. In some cases the voltage spikes were large enough and long enough to trip the protective circuitry on the system. Information on this issue was sent to SAFT, which provided SCS with a possible way to correct the problem. Since the fluctuations were initially reported, however, they have only re-occurred once and their occurrence did not affect a test series. If the fluctuations continue to occur, SCS will implement SAFT's recommended solution to see if that corrects the problem.

Difficulties were encountered when trying to establish communication between the system's PCS and the microturbine. It was determined that a conflict exists in the way that COM ports are assigned by the PCS and the microturbine. The PCS software is being updated to address the COM port configuration issues and the problem is expected to be resolved soon.

SCS completed several reference tests of the BESS at various loads (7.5, 15, 30, 60, and 100 kW). The figure below shows the system's discharge profiles for this test series. The next test series will evaluate the system in standalone mode without the microturbine. The system's response to voltage sags, grid interruption, and other power disturbances will be examined.




**Discharge profiles for BESS reference test series.**

## ***PV/Hybrid Controller Field Testing and Data Analysis***

| | |
|---|---|
| *SNL Contact:* | Garth Corey |
| *Contractor (Testing):* | Arizona State University (ASU) — Bob Hammond |
| *Contractor (Data Analysis):* | Electrochemical Engineering Consultants, Inc. (EECI) — Phil Symons |

**Project Overview**

In 1997, the ESS Program proposed to the Arizona Public Service Company (APS) that it sponsor a one – three year program under field conditions of a Hybrid Power Processor and Control System (HPPCS) for optimizing operational strategies of a 30 kW diesel, battery, and PV hybrid renewable energy system. APS would conduct the testing at its Solar Test and Research Center (STAR). Using a 30 kW inverter/ controller, on loan from the Sandia National Laboratories DETL (Distributed Energy Technology Laboratory), the project was designed to generate valuable operational data for APS which would allow it to assess the commercial viability of a packaged hybrid system for off-grid applications.

Using a Campbell Scientific, Inc. CR-9000 Data Acquisition System (DAS), also supplied by SNL, EECI was contracted as the primary analyst and consultant for the project and was responsible for generating quarterly reports to evaluate the effectiveness of the operational strategies employed by the Trace inverter/controller. From its inception, data collection for the hybrid system was hampered due to random periodic faulty operation of the DAS. In March 2000, the problem was resolved and random shutdowns were eliminated.

The Yuasa DGX tubular gel batteries used for storage in the hybrid system proved to be highly reliable and predictable. However, problems with both the 30kW and 80 kW generators, and unavailability of the periodically used load bank at Carol Springs Mountain, resulted in unachievable daily load profiles for the system well into 2000.

The major goals of the test program were met; but, funding limitations on revising the control firmware prohibited modifications for upgrading the controller to eliminate the shortcomings in the initial control philosophy that had been identified during the initial test program. Without these modifications, there would be little or no new information on the optimization of operational strategies for off-grid hybrid power systems. Continuation of funding would have extended the test program in order to determine the final optimal control strategies.

The Trace 30 kW inverter/controller was, therefore, returned to SNL in June, 2000. However, due to the high reliability of the Yuasa tubular gel battery, SNL requested and was granted a loan of the battery so that data collection and analysis could continue at the SNL Photovoltaic Systems Evaluation Laboratory (PSEL), where it was installed in the identical configuration that was used at STAR and continues to function at Sandia as an internal project.

Although the ESS Program is not currently utilizing the STAR facility, it continues to function as a Hybrid Test Facility for APS.

## ***Natural Gas-Fueled, 5kW, Continuous Power Fuel Cell***

*SNL Contact:* Garth Corey
*Contractor:* Plug Power — David Rollins

**Project Overview**

Fuel cells are referenced as an energy storage component in the DOE Energy Storage Systems Program (DOE/ESS). Therefore, it is important to understand how fuel cells operate in the distributed energy resources (DER) environment. Late in FY02, under a "cradle-to-grave" procurement contract with Plug Power, ESS acquired a 5 kW Plug Power SU1 CHP (combined heat and power) fuel cell for testing at the Distributed Energy Test Laboratory located at Sandia National Laboratories (Sandia DETL). The fuel cell, which has the capability to operate grid-tied or stand-alone, will be operated and tested in both configurations.

The purpose of this program is to characterize the fuel cell for operations above 5000 ft altitude and provide performance data for both on-and-off-grid operations. The fuel cell will also become a power generation component in the DER test program and will be connected to the DETL Micro Grid after characterization is complete.

Under provisions in the contract, two Sandia personnel who were trained in the system installed the Plug Power SU1 CHP fuel cell at the DETL early in the second quarter of FY03 and continue to operate and maintain it with technical support provided by Plug Power.

The unit went on-line at an output of 2.5 kW, with power being dispatched to the grid, and shakedown testing was completed early in the third quarter. Further testing was completed that replicated the factory acceptance tests. These tests provided characterization data for operation of the unit at high altitude. During the third year of the contract, the fuel cell unit will be upgraded to the most recent advancement in hardware and software to maintain the system at the current state of the art.

Problems with low power output were experienced late in the third quarter of FY03, caused by an operational algorithm that did not fully account for operation at the DETL's high altitude. Coordinating with Plug Power, Sandia engineers analyzed the problem and implemented changes that brought the unit back to full power. Planning was initiated to test the unit in an off-grid application to determine the transient response of the fuel cell.

The system operated sporadically at low power throughout the fourth quarter of FY03. Late in that quarter, the fuel cell stack was replaced and the system was brought back on-line. However, change-out of the stack did not solve all of the power problems and interaction with PlugPower continued through the end of the quarter, in an effort to restore the unit to full operation.

**First Quarter Status**

Due to FY04 funding shortfalls, the fuel cell program was put on hold in hopes that it can be resumed in FY05 to complete the three-year testing program.

## ***California Energy Commission/DOE Energy Storage Initiative***

*SNL Contact:* Garth Corey
*Partner:* California Energy Commission (CEC) — Pramod Kulkarni

**Project Overview**

The purpose of the CEC/DOE Energy Storage Initiative is to demonstrate electric energy storage (EES) as a technically viable, cost-effective, and broadly applicable option for increasing the reliability of the electricity system and for electric energy management in California and the nation. Sandia's roll will be to obtain, analyze, and disseminate data on energy storage system performance for all the CEC/DOE Energy Storage Initiative demonstration projects scheduled to be commissioned in the State of California during CY2004 and CY2005 under sponsorship of the CEC and DOE.

During FY02, the California Energy Commission (CEC) and the DOE formulated a plan for an energy storage initiative that would consist of up to six, California-sited demonstrations of energy storage applications, with $5M of funding provided by the CEC. The DOE ESS Program, through SNL, would provide expert technical consulting support for the project. The CEC would provide all administrative support for the project; while DOE/Sandia would provide all technical support.

The initial CEC/DOE Energy Storage Initiative Workshop was held at the Public Utility Commission in San Francisco, California on September 4, 2002. Approximately twenty, personally-invited, utility industry representatives and customers attended to discuss the overall demonstration program and to help set the ground rules for the forthcoming Request for Proposal (RFP).

In the winter of 2003, a public meeting was held at the CEC offices in Sacramento to initiate a public discussion of the terms of the planned RFP. This meeting helped determine the final structure of the technical requirements of the RFP. Much of the activity during the third quarter of FY03 was related to the development and writing of the RFP at several meetings in Sacramento.

Following the issue of the RFP on July 31, 2003, the CEC received 14 “intent to bid” responses. A pre-bid conference was held at the CEC offices in Sacramento the following August 21st. More than 50 persons attended the meeting, during which many aspects of the technical and administrative terms of the RFP were discussed.

As of October 20, 2003, seven bids had been received by the CEC and several meetings were held to review them. Of the original submissions, three did not meet the minimum bid requirements.  The remaining four proposals were submitted to the CEC/DOE scoring team for final review.

Contracts for the successful bidders are expected to be placed in early spring.  After contract award, each demonstration will operate under CEC/DOE/SNL monitoring for up to three years.

### First Quarter Status

On December 5, 2003, an announcement was made by the CEC that three projects had been selected for contract award:

**Palmdale Water District, Palmdale, Calif.**  A project to minimize the impact of variable winds on a 950 kW wind turbine attached to the Palmdale, CA, Water District's treatment plant microgrid by using a 450 kW Maxwell supercapacitor.  During power outages, energy storage will also provide ride-through for critical loads until emergency generation can be brought on-line.  While providing reliable energy for the microgrid, the project will, in turn, aid in reducing transmission and distribution congestion in the Palmdale area.

**ZBB Energy Corporation, Menomonee Falls, Wis.**  A project to reduce distribution system congestion by placing a 2MW, 2MWh zinc-bromine battery at a PG&E (Pacific Gas & Electric) substation.  The battery installation will be operating in a stand-by mode to supply extra power when the substation reaches overload conditions.  The installation will be mobile so that it can be deployed wherever the most serious peaking loads occur.

**Urenco Power Technologies, San Francisco, Calif.**  A project to deploy a 400 kW flywheel system on the San Francisco MUNI rail system to recover energy currently lost by trains when they brake.  The flywheel system will store the energy generated when a train brakes for a station stop; and then return that stored energy to the tracks as the train accelerates from the station, which will produce a 20% reduction in energy purchases for the supported track.  Other benefits include reduced energy impact on customers who rely on the same power grid source as the trains, plus the potential to alleviate distribution congestion on the San Francisco peninsula when more trains are deployed.

## ***Vernon & Metlakatla VRLA Battery Monitoring***

*SNL Contact:* Rudy Jungst
*Contractor:* Exide Technologies, GNB Network Power Division — George Hunt, Rob Schmitt

### Project Overview

VRLA (valve-regulated lead-acid) battery systems have been in place at the GNB Battery Recycling Facility in Vernon, California, and at the village Metlakatla, Alaska, for several years.  The BESS (battery energy storage system) at the Vernon smelter, a battery-recycling center, was first installed in 1995 (Figure 1).  It consists of two strings of 378 modules each of 4800-Ah Absolyte batteries (9600-Ah on site).  The BESS for Metlakala Power and Light (MP&L) was installed in 1996 and consists of one string of 378 modules of 3600-Ah Absolytes.

The different use profiles in the two locations provide a unique opportunity to compare two very similar types of VRLA cells in different use environments. Vernon continued to peak-shave at 3150 kW on weekdays during peak demand times (currently 16:00 to 22:00 PST); and Metlakatla is always on-line, reducing fuel consumption on the island to virtually zero.

As of FY03, both batteries had reached an age where it was desirable to do more extensive monitoring of their condition and operation to determine whether life expectations were being met. Therefore, a contract was placed to continue monitoring battery performance at Vernon and begin a more formal tracking of operational data at Metlakatla. In addition, periodic postmortems of modules returned to GNB from both locations were resumed to assess how much degradation had occurred and estimate the remaining battery life. Previously, only cells from MP&L had been removed and returned to the lab for testing.

**BESS Installed at the GNB Lead Recycling Center in Vernon, CA**

Extensive electrical testing of a second set of 100A25 cell samples culled from the Metlakatla BESS was completed at the GNB Fort Smith, AR plant during FY03. Results of capacity tests on cells cycled at several discharge rates showed that the cells continued to perform extremely well after six years in a partial charge application. Even at rates as high as one hour, compliance to the published capacity ratings was excellent.

A report on the postmortem analyses of Metlakatla battery components was also received. As of the end of FY03, the battery was aging normally for the type of environment it is in and appears to be on track to achieve its eight-year design life.

Twelve test cells were also replaced in the Vernon BESS and shipped to Fort Smith for similar testing. A detailed test request was prepared for this teardown and analysis, but the teardown was postponed until FY04.

The Metlakatla and Vernon batteries are nearing the end of their warranty period. A draft letter is being internally circulated regarding the future of the Vernon BESS. (The unit is wholly owned by GNB-Exide.) GNB-Exide will seek funding for repair and maintenance of the battery and electronics from internal and external sources. Similarly, George Hunt is preparing a proposal for replacement of the Metlakatla battery, which is wholly owned by the MP&L utility.

### First Quarter Status

A paper summarizing the results of the electrical tests and teardown analysis during FY03 of the batteries pulled from the Metlakatla BESS was presented at the EESAT Conference in October 2003.

The conclusion of this real time aging study was that continued operation of the Metlakatla battery at partial state of charge has not caused an early end of life. In fact, the battery capacity is stable and it appears that its eight-year design life will easily be achieved. Internal examination of the Metlakatla cells also continues to show unexceptional results. Grid corrosion has been lower than expected; while analysis of the active materials indicates normal compositional and structural characteristics for a cycling application. The VRLA battery has been shown to be viable in this unconventional charging regime.

Postmortem of cells from the Vernon battery is still on hold. Due to uncertainty of funding levels in FY04, it was decided to wait to conduct the physical analysis on the cells returned to Ft. Smith in FY03 until the level of available funding was known.

## ***Evaluation of Utility Scale System — TVA Monitoring***

*SNL Contact*: Georgianne Peek
*Contractor*: Electrotek Concepts— Dan Sabin

### Project Overview

The Tennessee Valley Authority (TVA) is constructing a large-scale, battery-like power storage facility designed to store electricity during off-peak periods and retrieve it for use when the need for power increases. Using technology developed and provided by Regenesys™ Technologies Limited, of the United Kingdom, the plant is designed to store up to 120 megawatt-hours of energy and provide power for 10 hours.

Initiated in FY02, this project is designed to provide the data collection management, data and economic analyses, and dissemination of the data on the performance of the TVA Regenesys™ Electrical Energy Storage System. On 2/19/03 a meeting to kick off the monitoring project was held at the TVA Regenesys plant site in Columbus, Mississippi.

The goals of the monitoring project are:

- To look at the entire system as a black box power storage system and gather the data necessary to characterize it’s operating characteristics from both technical and economic points of view in all operating modes

- Evaluate the impact of facility on power system operation, line loading, and capacity.
- Evaluate the impact of the facility on power system quality and reliability.
- Be able to extrapolate project results for future plants.

TVA seeks to learn the following from the monitoring project and ensuing data analysis:

- Identifying the value streams – which operating modes are more important and why (e.g. arbitrage, time shift, ancillary services, a combination, etc.).
- Determine how well the plant performs while providing these various services; identify limitations and constraints.
- Determine availability and reliability.
- Determine overall plant efficiency.
- Repeat identical tests over time to determine if there is any degradation of the system.
- Determine how energy storage might fit into the standard market design.
- Identify how Regenesys™ technology might be employed to augment intermittent renewable resources (e.g. wind, photovoltaics)
- Help identify attributes necessary for TVA to decide on when/where to deploy similar plants.

Electrotek is creating a project plan for the data collection and analysis, which includes setting up an electronic data collection site. They outlined the system and are currently working out the firewall issues.

In May, TVA decided to put the Regenesys project in Columbus, MS on hold. Their project plan included implementing lessons learned from the Regenesys system being installed in Great Britain. That installation has been delayed due to startup items.

TVA and Regenesys had planned to restart TVA Regenesys in the October to December timeframe; however, the project was put on indefinite hold during the fourth quarter of FY03.

**First Quarter Status**

The TVA Regenesys project was canceled during this quarter. The parent company of Regenesys has decided that this technology is not one of their core businesses and they will no longer support it.

TVA is currently looking into alternatives for meeting the energy storage requirements at the Columbus AFB site.

## ***NAS™ Battery Demonstration Monitoring***

*SNL Contact*: Georgianne Peek
*Contractor*: Gridwise Engineering– Ben Norris

**Project Overview**

The goal of this project is to obtain, analyze, and disseminate data on the performance of the Sodium Sulfur (NAS™) battery electrical energy storage system currently being installed at an American Electric Power (AEP) site, in Gahanna, OH, a suburb of Columbus. The demonstration is composed of two NGK Insulators Ltd., NAS battery modules that will provide up to 500 kW of power quality protection for five minutes, plus 100 kW of peak shaving capacity for seven hours per day.

**Sodium-Sulfur Battery**

Operations to perform the data and economic analyses began in January 2003, under a contract with Gridwise.

The following March, the goals of the monitoring project were reviewed at a meeting among SNL, AEP, Gridwise Engineeringr, and Endecon Engineering. At that meeting, it was determined that Gridwise would perform a reliability analysis related to the power quality service, to include some indicator that reflects loss of life. The economic analysis was also expanded to include the power quality issues of peak shaving (customer and utility), spinning reserve, voltage support, and T&D deferral. Gridwise agreed to prepare their project plan based on the results of that meeting.

During the progress meeting held in May 2003, Gridwise presented the plan for the data analysis portion of the project and the attendees decided that the plan should also include confirming operation of the unit during PQ events because of the difficulties in calculating the DC energy of PQ events, which would introduce some error into the overall DC energy calculations from the database.

Gridwise also presented the plan for the economic analysis. The attendees decided that the Gridwise economic analysis plan should use data from AEP customers of various classes in addition to the Gahanna site, plus data from two other meters in the Gahanna campus.

Later that month, SNL, Technology Insights, NGK, and Gridwise met and addressed the issue of monitoring loss of life. They decided that the mean value over the course of the discharge (or charge) would be the best measure for a methodology, based upon data from the database, to calculate the “mean internal resistance” for each cycle as a figure of merit for degradation.

At the May 2003 ESA meeting in Chicago, AEP reported on several problems concerning the operation of the NAS unit that arose during the second and third quarters of FY03, which have either been corrected or are in the process of being corrected (For details of those issues, see Quarterly Progress Report for Third Quarter, FY03).

Gridwise presented the Preliminary Data and Economic Analysis Reports on September 18th.

Thus far during its operations at Gahanna, the NAS storage device has operated in three different power regimes: A 175kW/1300kWh per cycle regime until the end of October 2002; an 88kW/620kWh regime (Regime 3) until mid-May 2003; and a 100kW/385kWh regime (Regime 1) from mid-May to Sept. 2003.

The peak battery bottom temperature was limited to approximately 350ºC until the latest operating regime started. Starting mid-May 2003, the temperature was limited to approximately 332ºC, which will allow higher power levels during PQ operation, but will shorten the life of the batteries. Some data anomalies were noted that warranted additional investigation. The single-line diagram of the AEP NAS Demonstration system is shown in the figure below.

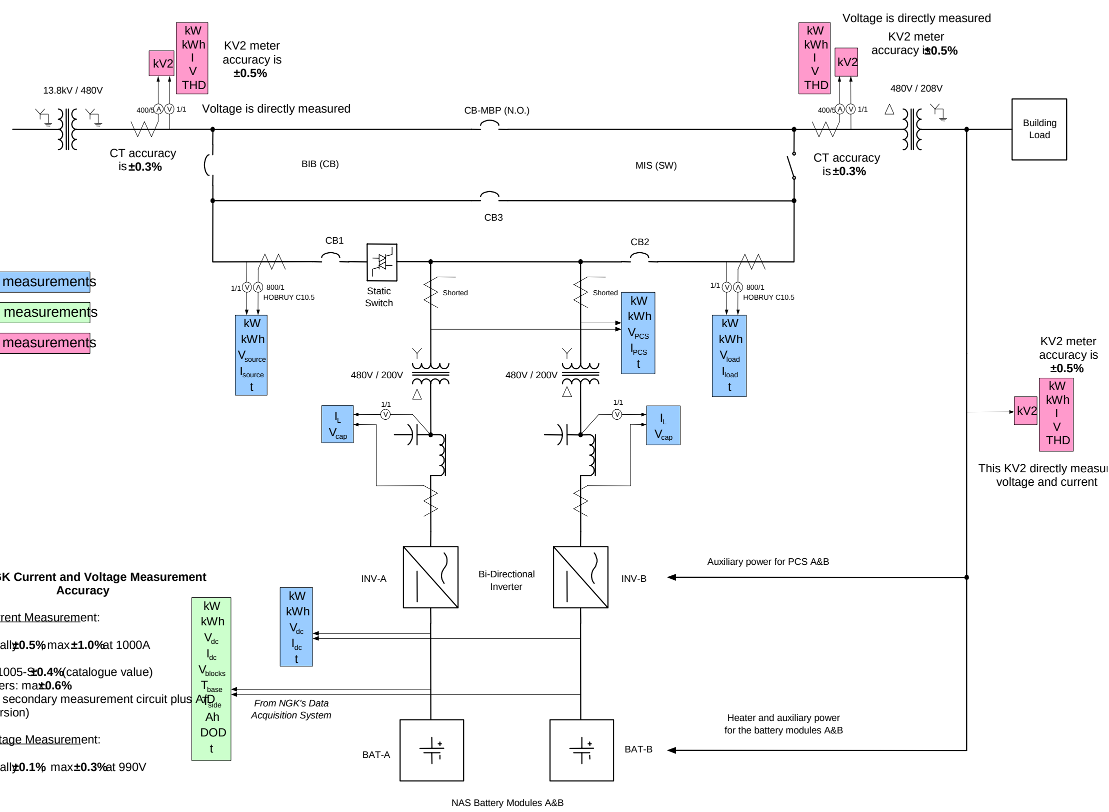



**Figure 1. AEP NAS Demonstration Project One-Line Diagram**

However, thus far in its operations, the principals have arrived at some preliminary conclusions about the NAS battery system. They include:

Energy Shifting

The NAS energy storage demonstration project has so far shown that it can implement energy shifting from nighttime to daytime while maintaining a reserve capability to provide full load support in the event of loss of grid.

System Efficiency

System efficiency is one way of identifying the cost of implementing displacing energy from off-peak to on-peak hours. The lower this efficiency is, the greater the cost differential between on and off peak times must be before the displacement can be economical. Because the auxiliary heating function significantly reduces the efficiency, even when the system is operating as designed; a simple way to reduce auxiliary power consumption might not be possible unless additional insulation can be introduced.

Load power interruptions

Load power interruptions likely to cause disruption of operation have so far occurred with more frequency than similar grid power interruptions. AEP and ABB are continuing to identify potential improvements in design needed to resolve these interruptions.

NAS Operating Schedule

Depending on which operating regime is used, the preliminary analysis showed that the NAS operating schedule would need to be adjusted in order to align it with on-peak intervals used by typical electric power tariffs. Doing this will assure that either displaced energy and/ or peak load reductions will be maximized.

When the NAS is operated at high energy displacement levels, some tariffs might limit the off-peak time to such an extent that the NAS cannot be charged during the off-peak time; therefore, not all combinations of operating regimes and tariffs will make sense.

**First Quarter Status**

On November 18, 2003, a meeting was held among Sandia National Laboratories, AEP, Technology Insights, and NGK Insulators to discuss the performance issues identified in the preliminary analysis report. Following are the results of the meeting.

The possible formulas for calculating efficiency were discussed. All parties agreed that energy-out divided by energy-in is acceptable. NGK proposed a method for “corrected efficiency”. The assumptions included 100% coulombic efficiency and some mathematical simplifications. Jeff Braithwaite will be consulted.

The NGK measurements are two-second averages for both current and voltage. To determine the actual accuracy for lower peak shaving currents, AEP will verify NGK’s CT accuracy over one cycle. After this test, the participants will decide if either new CTs (or LEMs) are required, or whether to use the existing CTs and correct measurements during analysis by using correction factors derived from the test.

Total auxiliary loads are roughly 90 kWh for Regime 3. PCS sized for 500 kW, but this could be reduced to optimize efficiency for peak shaving. For continued testing, it was decided to use Regime 3 since Regime 1 has lower efficiency (See Table below). To change, there are two options: (1) reduce vacuum; or (2) lower operating temperature from 325C to 305C. Option (1) would increase the heat loss (lower efficiency) and allow 5X PQ. Option (2) would decrease heat loss (higher efficiency) and allow 3X PQ. AEP decided to pursue option 2, and NGK will come to the site to implement.

Dan Mears suggested using the EPRI Handbook for publicly available capital cost and other data. (Use mid-year 2006 cost). Also, expand analysis to include non-AEP tariffs that look more attractive for peak shaving.

It might be desirable to add additional metering to isolate the static switch losses — this idea was not discussed at the meeting, but is included here for discussion. A kV2 meter could be placed immediately on the load side of the static switch. This would allow the losses to be tabulated, so that separate values could be obtained for (1) static switch; (2) AC/DC/AC losses; and (3) auxiliary loads.

**NAS Operating Regimes Tested**

| Operating Regime | PQ Protection | PQ Factor | PQ Interval | PQ DC kWh per PQ interval per battery | PS DC kWh per battery[1] | # PS Cycles Over Life | Operated Interval |
|---|---|---|---|---|---|---|---|
| 1 | 30s | 5.0 | 1 hour | 2.2 | 210 | 1500 | 5/2/03 to present |
| 3 | 30s | 3.0 | 1 hour | 1.3 | 375 | 2500 | Installation to 5/2/03 |

On Dec. 16, 2003, Ben Norris and Georgianne Peek met with Jeff Braithwaite, who is a subject matter expert on NAS batteries. He confirmed that the coulombic efficiency of NAS batteries is essentially 100%. Catastrophic failure is the only reason for less than 100%. This is not the case at the AEP Gahanna site, which means there is a problem with some of the sensors. Based on theses results AEP and NGK will test and change out the sensors.

In addition, the power electronics efficiency must be less than was indicated in the preliminary analysis report, because the power electronics and DC battery measurements from the KV2 meter are tied together. We have requested that AEP isolate the static switch losses to provide an additional level of performance breakdown.

## ***Alaska Battery/Diesel System Model***

*SNL Contact:* David Trujillo
*Contractor:* Sentech — Rajat Sen

**Project Overview**

Alaska offers significant opportunities for the introduction of energy storage into distributed resource electricity supply systems. One such opportunity is in progress by the Alaskan Energy Authority (AEA). The two entities have developed a battery-diesel system model designed for reducing fuel consumption, increasing performance, and improving the rigor and reliability of power in remote Alaskan villages.

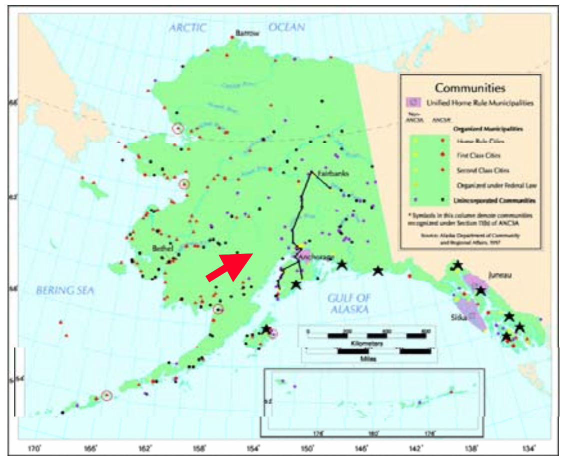



**Figure 1. Site of Test Bed Solar/Diese/Battery System in a Remote Area of Alaska**

Provided for in a contract with Sentech, the model ("HybSim") concentrates on the feasibility of coupling battery energy storage systems with existing diesel generators (including photovoltaic hybrids in some cases) to evaluate different scenarios for using battery storage with small, stand-alone diesel generator sets (gensets). Modeling and analyses reveal that benefits can be gained from a storage-diesel system.

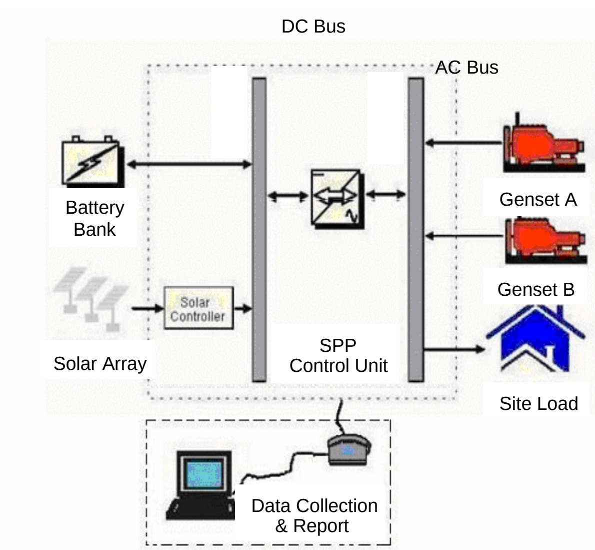



**Fig. 2: Diagram of Model Solar/Diesel/Battery System**

During FY01, HybSim was converted to modular code architecture (Fig. 2) and SNL provided technical and financial support to AEA for completion and installation of a photovoltaic (PV) system to an existing battery storage/diesel genset system in Lime Village, Alaska (See below: ***Alaska Battery/Diesel/PV-Hybrid Test Bed System (Lime Village)***. Based on analysis, SNL reasoned that data from this project would be beneficial not only for identifying power needs at Lime Village but also for validating HybSim.

Under a new contract with Sentech in FY02, PV analysis capability was incorporated into HybSim and the resulting performance validated. Upgrades and enhancements to the model were added and, under a new contract between Sandia and AEA in FY03, detailed feasibility studies were instituted, which would lead to the design, fabrication, installation, and testing of a prototype system during FY04. Code development was also completed and incorporated, which allowed Version 1 of the model to perform an analysis and determine an optimized system, to be incorporated into Version 2.

Testing and validation of Version 1 continued throughout FY03, which included technical performance of the model and user testing for feedback on ease of use with the interface. Additional PV capabilities were also incorporated and are undergoing continuous testing and validation. A user manual was incorporated into the software in the form of 'help' files. Final revision of the model's capabilities came close to completion during the previous quarter.

In response to a failed battery system at the Lime Village Test Bed project, HybSym correctly analyzed the technical and economical issues at Lime Village in an effort to determine an optimal replacement system. HybSim also analyzed power factor corrections, improved balanced loading, and inverter upgrade/corrections to maximize output and help optimize battery charging. HybSim demonstrated, therefore, its value as a potential tool for technical and economic village analysis for local co-ops, the AEA, and power companies that own/manage village power systems.

A workshop was conducted on August 28, 2003, designed to commercialize the software and establish a set of Alaskan users willing to participate in beta testing the model before release of "HybSim, Version 1." Fourteen local Alaskan stakeholders in village systems attended, plus four outside entities. All participants commented very positively on the potential usefulness of the model in their own applications, and 70% of the local participants agreed to beta test the program.

Once all of the improvements have been thoroughly tested and validated, the model will be ready for application in identifying promising sites for hybrid system installations. It will also be available for interested parties to perform their own analyses and confirm the benefits of installing hybrid systems in other villages, as well as aid in sizing and configuring those systems.

The goal is to get the model into the hands of Alaskan agencies and establish a user base. We will then support the AEA by performing technical and economical analyses for system improvement for one to two village systems identified by the AEA. Plans also include full support of the annual AEA Energy Conference through participation and technical support of seminars.

With continued support and methodical effort, the model can become a viable tool for the Alaskan communities.

### First Quarter Status

Project prioritizations were completed. The Statement of Work for FY04 was prepared and approved. Initiatives for FY04 will include the incorporation of relevant comments from the August 2003 workshop in Anchorage, model validation, implementation of a user test plan for potential Alaskan users, improved seasonal data, load growth algorithms, enhancements to windows and library data controls, and improved dispatch routine capability.

## ***Alaska Battery/Diesel/PV-Hybrid Test Bed System (Lime Village)***

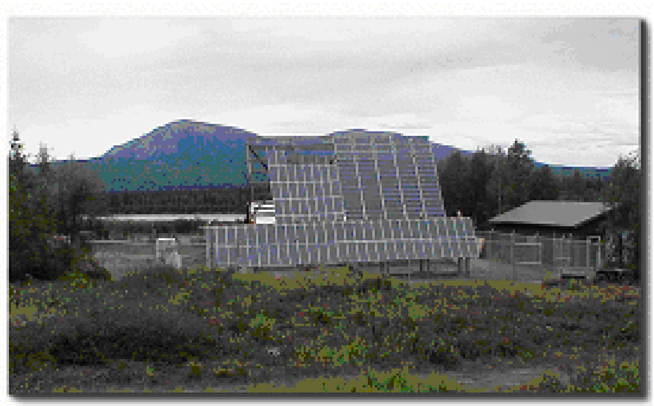
*SNL Contact:* David Trujillo
*Contractor:* Alaska Energy Authority (AEA) — Peter Crimp

**Project Overview**

In concert with the results from a collaborative modeling effort (See above**:** *Alaska Battery-Diesel Model System*), Sandia National Laboratories (SNL) and the AEA have agreed to install battery storage systems with small, stand-alone, distributed diesel generators (gensets) and photovoltaic (PV) arrays in a remote Alaskan community named Lime Village

Managed and funded by AEA, the Lime Village project is designed to both provide the community of Lime Village with reliable and affordable electricity and to validate the Battery/Diesel/PV model described above. Lime Village is a reconfiguration of the established prototype diesel-hybrid system. The system is coupled with an expanded PV array and a new, smaller diesel generator set that will provide the opportunity for collecting real time data on Alaskan Village hybrid systems for further modeling development and optimization of technical and market analysis.

The AEA believes the battery/diesel/PV approach will provide the community with optimal fuel savings and regards the potential success of this test-bed project as a model for expanding opportunities to other Alaskan villages with similar needs. McGrath Light and Power, on behalf of the Lime Village Traditional Council, will perform the actual construction, operations and management of the system.



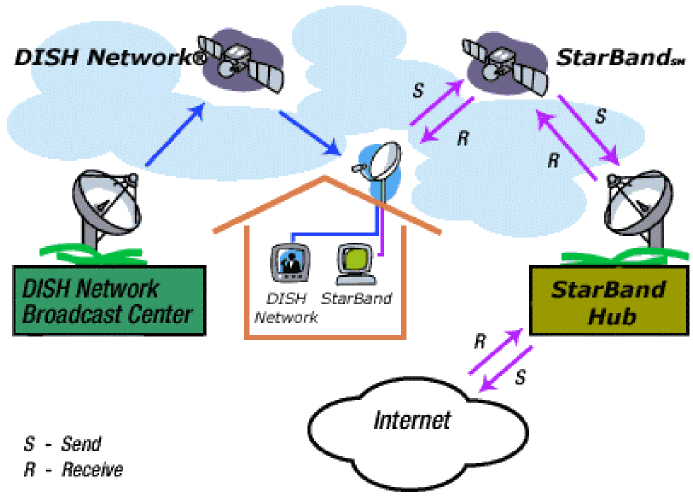
Lime Village Test-Bed: Typical Expanded Solar Array

Technological and funding limitations had prevented the purchase of a suitable inverter and the development of a scheme for system integration. With the assistance of Sandia National Laboratories, however, all major system components, except the inverter,were purchased and installed.

Lime Village Test-Bed: Typical Diesel Generator

During FY02, a contract with McGrath Power and Light was put in place for the installation of sensors and meters and maintenance of Lime Village systems in support of test bed availability. Installation of some of the key meters and sensors was also completed.

A separate contract established data acquisition and reporting during the second quarter. A Starband Communications System (see illustration below) was installed, which provides the capability to transmit the test bed data to the Internet. Lime Villagers have been trained in the operation and maintenance of the system.




Data Transmission Using Starband Communications System

Under contract, and overseen by SNL and the AEA,UAF designed and installed a reliable data-retrieval interface for data transmission from the LV Test Bed that satisfies SNL requirements for the Lime Village project.

During FY03, fuel flow meters, a DC input and output current meters for each PV array were installed, which completes the majority of requirements to validate the Battery/Diesel/PV model.

The battery system in Lime Village began to fail during the first quarter of FY03. Therefore, negotiations began between AEA and McGrath to provide a replacement, with SNL offering technical support for specifications for the replacement system. Working jointly, SNL, Sentech Inc., the AEA, and McGrath Power and Light used the HybSim model (See above**:** *Alaska Battery-Diesel Model System*) as a tool to analyze the technical and economical issues surrounding the failed battery system. HybSim revealed solid approaches for resolving the Lime Village problems, such as power factor correction, improved balanced loading, inverter upgrade/corrections to maximize output and help optimize battery charging, and an optimal battery replacement system. By the end of the fourth quarter of FY03, the system was awaiting an upgraded inverter and battery replacements.

## First Quarter Status

Project prioritizations were completed. The Statement of Work for FY04 was prepared and approved. Initiatives for FY04 will include supporting the AEA with the Lime Village battery replacement in which the HybSim analysis provided input for the optimal system given the current technical and economical factors at LV, maintain the remote data retrieval web sites, and maintain the test bed environment for HybSim.

# SUB-SYSTEM DEVELOPMENT

## *Alternative RGS System Designs to Improve Battery Performance*

*SNL Contact:* Stan Atcitty
*Contractor:* Electrochemical Engineering Consultants, Inc. (EECI) – Dr. Philip C. Symons

**Project Overview**

The purpose of this alternative configurations project is to develop and validate integrated devices that will improve system reliability and component performance, and reduce the life-cycle-costs, of continuous power systems such as renewable generation systems (RGS). Thus far into the project EECI has designed and built 10 kW and 100 kW ACONF units. The high power (100kW class) units that have been developed have a capability of 33 kW for each string, and incorporate a relatively low-cost, novel approach for providing power for finish charging.

Currently, the primary objective of this project is to provide a means to optimally manage the charging and discharging of the energy storage batteries in RGS solar-hybrid systems. Secondary objectives for the work include improving the communications among battery suppliers, power converter developers, and customers; and evaluating the utility of the methods developed in the work to other battery applications, such as provision for standby power.

Work began on this project during the fourth quarter of FY98, when several alternative configurations were conceptualized and modeled to verify that the design concepts would lead to improved system performance for batteries in hybrid power systems and that might ultimately reduce life-cycle-costs.

Following the construction and testing of some laboratory and breadboard systems, prototypes of one of the alternative configurations (called ACONF) were built and tested, to validate the modeling work, during FY99 and through FY00. The first prototypes developed were designated as 10 kW class units.

In FY01 and FY02, three copies of the most-advanced prototype were built. Since 2000, two of the 10 kW prototypes are being tested at the Arizona Public Service Solar Test and Research (STAR) Facility in Tempe, AZ. The third was installed at the Sandia National Laboratories (SNL) Photovoltaics System Evaluation Laboratory (PSEL) and is undergoing testing there with a 24V AGM VRLA battery. The STAR Facility is owned and operated by Arizona Public Service, which has several semi-commercial PV hybrid sites.

In FY03, development work on the ACONF concepts continued in the laboratory, and testing and refinement of the 10 kW class units at the three sites continued. In addition, a 100 kW class prototype ACONF unit was developed, and two different variations of the basic design, one with semiconductor switches and the other with electromechanical relays, were factory tested at the sub-contractor who assembled the two units. The 100 kW units began testing at APS STAR in 2000 and have operated reliably, one for almost three years and the other for close to two years, even during the extremely hot summers at that location. Data is collected weekly from the ACONF units at STAR before being sent to EECI for analysis.

### First Quarter Status

No major issues with the ACONF units were identified during the 1st quarter of FY04, although the analyses showed that one of the battery strings in one of the STAR test systems was not performing as well as it had done in the past. APS personnel will address this problem as their schedule permits. The poor contact problem identified in the 4th quarter of FY03, which had been thought to be associated with the ACONF printed circuit board, turned out to a mechanical failure in one of the shunts used to measure string currents. This failure resulted from installation of the shunt by inexperienced personnel, and had nothing to do with the ACONF unit *per se*. Testing of the 10kW class units will continue in the remaining part of FY04.

Testing of the 10kW ACONF unit at PSEL with VRLA batteries has been suspended temporarily pending definition of an appropriate test schedule. Data obtained previously will be used in setting up a comparative test on the 10kW class ACONF unit, to be conducted for the US Coast Guard later in FY04. This “Work for Others” project, funded mostly by the Coast Guard, but with some DOE co-funding, represents the first sale of the ACONF technology and marks a high point in the project. Results from the Coast Guard testing will be documented in future quarterly reports (See: *United States Coast Guard, National Distress System, Electric Power System Optimization Study)* .

The primary focus of work on the ACONF project in FY03 was development of a high-power (100kW class) unit. A photograph of one of the 100kW class units that was developed, designated Unit 2B, is shown in Figure 1. This unit was installed at the Sandia DETL late in FY03, in preparation for testing there.

**Figure 1: ACONF Unit #2B at DETL.**

The high power (100kW class) units that have been developed have a capability of 33kW for each string, and incorporate a novel, relatively low-cost, approach for providing power for finish charging. Unit 2B at DETL is set up for operation with a two-string, VRLA gel battery (manufactured by Yuasa in 1996) and is rated at 33kW. The battery is connected to a Xantrex (Trace) converter rated at 30kW (480V 3-phase AC) that is connected to the grid in lieu of a generator, and for which there are a variety of load banks that can be connected for testing as necessary. A solar PV array can also be connected to this system when required.

Testing of Unit 2B at the DETL was continued for much of the first quarter of FY04. Initial testing showed that the unit operated satisfactorily; but improvement of the finish charge hardware and software was required before the unit could be put into automated testing. During the first quarter, the required improvements to the finish charge hardware and software were developed and implemented, and some automated testing was conducted. Figure 2 shows the results of one day of testing, during which a discharge of the Yuasa VRLA battery was completed; then, in sequence, a charge, a finish charge, and the beginning of a further discharge. Unit 3B, another high power unit fabricated and factory-tested late in FY03, was also modified to incorporate the refined finish charge hardware.


**Figure 2. Test Results for ACONF Unit #2B at DETL, 12/07/03.**

Although Unit 2B with the modified finish charge hardware and software was successfully tested for a month or so at DETL, there were several flaws in the design that became apparent when the unit failed shortly after the test shown in Figure 2. The failure damaged several of the internal components of Unit 2B. Analysis of the damage to Unit 2B, conducted in collaboration with Sandia ESS and DETL personnel, allowed a significant redesign of the high power units with relays to be made. It is believed that the redesign will address all the deficiencies of the previous design.

The redesign will be implemented on Units 2B and 3B early in the second quarter of FY04. After a successful period of test of Unit 2B at DETL, Unit 3B will be installed and tested in the APS STAR Facility Hybrid Test Building for further evaluation of the high power ACONF units.

## ***High Power Semiconductor Switch Development for PCS***

SNL contact: Stan Atcitty
Contractor: Virginia Tech (VT)—Dr. Alex Huang

**Project Overview**

Financial support to Virginia Tech from DOE ESS program started in April of 1998. The overall objective was to develop advanced semiconductor switches for the Power Conversion Systems (PCS) used to connect an energy storage system to the grid. Currently, this project is testing and evaluating switches operating at 1000 A, 2 kV, 1 kHz in continuous operation mode.

In 1999, funding for this project enabled VT to demonstrate the first generation (Gen-1) prototype of a low cost/high reliability/low footprint Emitter Turn-off (ETO)-based converter and the world’s largest MOS controller power switch (ETO 6 kV/4kA). In 2000-2001, Gen-2 ETO was developed and implemented in a high power converter targeting TVA’s application in dynamic voltage support. Also in FY02, DOE ESS support to VT and American Competitiveness Institute (ACI) enabled the demonstration of a manufacturable Gen-3 ETO, which was tested and evaluated at 1000A, 2kV, 1 kHz in continuous operation mode. Snubberless turn-off capability at 5000A of the ETO has also been tested and evaluated; and the reliability and lifetime of the ETO were improved by optimizing its capacitors. A Gen-4 ETO concept began in FY03.

**First Quarter Status**

In this quarter, VT continued the environmental test of the Gen-3 ETO. Using MIL-STD-883E and JEDECA104B as guidelines, VT subjected multiple ETOs to extended sustained temperatures of 85ºC, 100ºC, and 115ºC, plus temperature cycling from –40ºC to +125ºC. Repeated testing showed the design was robust at the sustained temperatures of 85ºC and 100ºC with an optical input of 1kHz. The overall current through the gate driver varied by less than 2% throughout the test period at these temperatures.

VT did see repeated, but recoverable, failures when operating at both a sustained 115ºC and during the temperature cycling. These results were as expected, in that the gate driver utilizes multiple electrolytic capacitors, which have a temperature rating of <= 105ºC. In all cases, the ETO performed as expected once temperatures returned at or below 100ºC.

An interesting observation: the connections themselves required some care, as the connectors (to power supplies, optical signals, etc.) would often become brittle at extended temperatures. VT addressed this issue by hard-wiring extensions from the board, then making the connections outside the oven.

VT presented the FY03 results at the EESAT 2003 Conference in San Francisco in October 2003.

Virginia Tech is currently awaiting FY04 funding for future activities.

## ***Manufacturing Process Development for High Power Semiconductor Switch***

SNL Contact: Stan Atcitty
Contractor: American Competitiveness Institute (ACI) – Mike Frederickson

**Project Overview**

The purpose of this project is to develop the manufacturing processes for the ETO device, a high power semiconductor switch assembly, designed by VA Tech (See above: *High Power Semiconductor Switch Development for PCS*).

The overall goal is to take the "engineering breadboard" design concept, and to effectively develop it into a commercially viable product. ACI's focus has been on the tasks of documenting the assembly procedures, processes, and bill of materials; designing the mechanical mounting components; analyzing the reliability and production costs; and performing a Finite Element Analysis (FEA) of both thermal and mechanical behavior of the ETO device assembly.

An additional task for fiscal year (FY03) was to review the cooling options applicable to the ETO assembly and their effect on performance.

One of ACI's goals was to achieve a high degree of manufacturing automation. Utilizing their demonstration factory floor, with the latest state-of the-art manufacturing equipment, ACI successfully developed that process and produced 24 alpha prototype high power ETO printed circuit board assemblies. They were delivered to VA Tech for evaluation. Automation improved the production rate from one device per day, using the hand assembly method of the engineering samples, to potentially 25 devices per day.

Five units were subjected to thermal stress cycling between +100 degrees C and – 20 degrees C (per JEDEC STD Test Method A106-A modified). No failures or any visual consequences were observed from the test results.

A Finite Element Analysis (FEA) for thermal and mechanical stress of the ETO assembly was performed using ALGOR analysis programs and the experience gained from the prototype fabrication.

In FY02, ACI expanded the documentation of assembly procedures, processes, and bill-of-materials from only the ETO PCB assembly, to include also all the mechanical mounting components, up through the "top level" assembly. With the assistance of VA Tech, a preliminary specification sheet was produced for the ETO device.

Mechanical parts for ETO assembly were designed using "SOLID WORKS 2001 PLUS" CAD Software and featuring a "top-down" design, specifically for automated assembly. The inherent reliability of the ETO assembly was analyzed per the MIL-HDBK-217F Standard using the “parts count method”. Material and labor cost data were also determined. Twelve analytical works were performed using ALGOR software.

In FY03, ACI performed a review of cooling options for “press pack” power electronic devices, including water-cooled heat sinks, air-cooled extruded heat sinks, heat pipe assemblies, and heat spreading techniques using graphite materials.

ACI and two of its vendors, Thermacore, Inc and k-Technology, Inc, met to discuss technical issues regarding cooling concepts and hardware applicable to the ETO assembly.

Several Finite Element Analyses (FEA) were performed using ALGOR software to determine the thermal response of the various configurations under reduced power applications, such as “circuit breaker,” low frequency switching, and load currents below 1000 amps. ACI focused on the analysis of thermal cooling solutions for the high power semiconductor switch assembly (ETO - Gen 3). Calculations of thermal resistances and junction temperatures were made for various configurations.

Costing information was gathered on several ETO cooling options including: 1) simple extruded aluminum heat sinks from Darrah Electric Company; 2) a combination of heat pipes embedded within a solid copper block with an attached heat fin assembly from Thermacore, Inc; and 3) commercially available complete water chiller systems.

Also investigated were some COTS materials for potential use in novel heat spreading design concepts. These included: 1) Annealed Pyrolytic Graphite from k-Technology, 2) Flexible graphite PGS sheets from Panasonic, 3) Graphite Foams from Poco Graphite , and 4) Bonding materials from S-Bond Technologies.

**First Quarter Status**

During the first quarter of FY04, ACI’s level of effort on this project was curtailed somewhat, due to a lack of funding support. However, several other currently active ACI programs offered leveraging of resources opportunities involving materials and interfaces for thermal management, and also packaging / reliability analysis of high power electronics devices and assemblies.

First quarter activities included:

(1) Technical interfacing of ETO thermal management analysis information with Prof. Alex Huang, at VA Tech, in support of his ETO project presentation for the EESAT conference.

(2) Generation of a concept paper: “Repackaged ETO Design for Advanced Power Switching Applications.”

(3) Participation in the 2003 R&D 100 Awards program.

(4) Continuing investigation of thermal heat spreading materials and interfaces through both ALGOR finite element analysis and lab experimentation.

(5) Evaluation and test plan development for qualification of “quick disconnect,” thermal cooling, and fluid couplings for high power conditioning modules.

## ***High Power Semiconductor Switch Performance Testing***

SNL Contact: Stan Atcitty
Contractor: Naval Surface Warfare Center, Carderock Division
Patrick J. McGinnis

**Project Overview**

This project is a joint effort between DOE, Sandia Labs, the US Navy, Virginia Polytechnic Institute, and the American Competitiveness Institute (ACI). It focuses on subjecting a prototype power semiconductor device designated the Emitter Turn-off Thyristor (ETO) to a series of operational and environmental performance tests. (See above: *High Power Semiconductor Switch Development for PCS*). The device is to be tested for a four (4) hour period at switching frequencies of 500Hz and 1000Hz, respectively, subject to a maximum junction temperature of ~ 115°C. It will also be subjected to a one (1) hour thermal cycling test to assess its operation and reliability at extreme conditions.

Figure 1- ETO Device

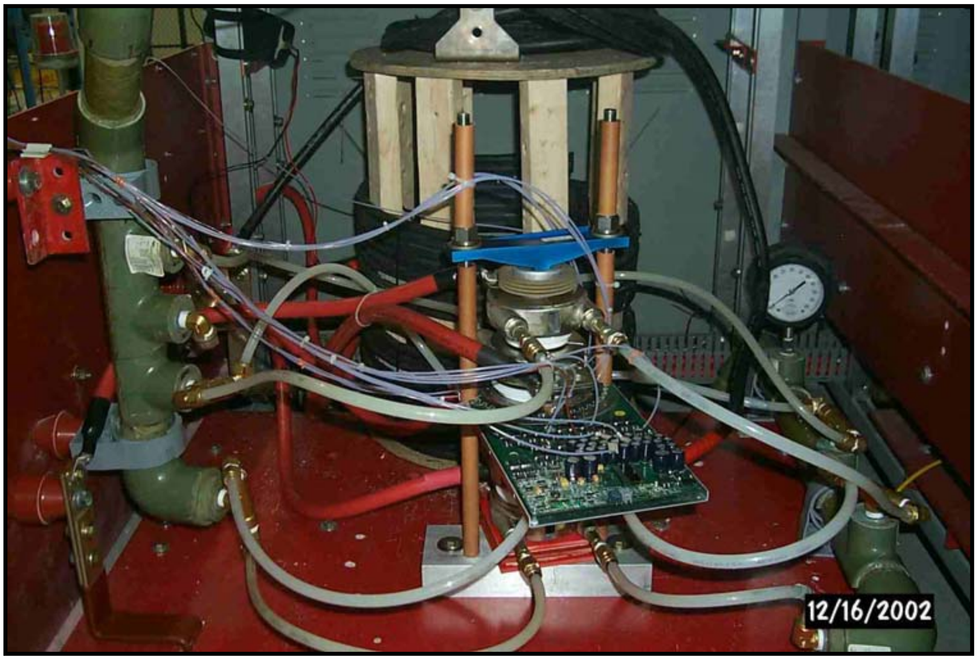



**Figure 2- ETO Stack - Test Set-up**

Prior Efforts

The project began in August 2002. Initial efforts through December 2002 involved identifying a suitable test location and modeling the test circuit; then procuring, manufacturing, and installing the necessary circuit components. Test cabinets were installed and facility wiring modifications completed and project personnel attended high voltage safety training. Test device #5 was installed and instrumented, and full scale testing began in January 2003; but was halted due to an equipment failure and a safety mishap.

Activities through March 2003 focused on remedial safety actions and test set-up upgrades, which were required prior to re-testing. Re-testing was started and subsequent troubleshooting of the power supply, data acquisition system and circuit components occupied most of the time through June 2003. The test regime was successfully completed in August 2003 with the performance of four-hour duration testing at 500 and 1000 hertz, along with a one hour power cycle test.

**First Quarter Status**

Activities in this quarter focused on analyzing the test data and supporting Virginia Tech's presentation of the ETO test results at the EESAT 2003 conference in October 2003.

Inputs were provided to DOE regarding FY04 plans for future testing efforts at higher power levels

Final test data was organized and forwarded to ACI and Virginia tech. A first draft of the final test report was prepared in cooperation with ACI and completed for initial review and comment by the end of December 2003.

Completion and delivery of the final test report, along with development of future high voltage test plans, are expected to occur in the remainder of FY04.

## ***Optically Isolated, HV/IGBT- Based, Megawatt, Cascaded Inverter Building Block For DER Applications***

SNL Contact: Stan Atcitty
Contractor: Airak, Inc. — Paul G. Duncan

**Project Overview**

Development of stackable topologies enables extremely high power systems to be realized and, when combined with optical voltage and current sensors, as well as optical control interfaces, enables a topology that greatly simplifies development within the high-power electronics environment. Airak, Inc., in conjunction with the Center for Power Electronics Systems at Virginia Tech, has developed the first optically isolated/interconnected, high-power cascaded (stacked) inverter for Distributed Energy Resource applications. Based upon recent advances in optical sensors, optical interconnects, and High-Voltage Integrated Gate Bipolar Transistors, the units are operating as expected through 320 kVA, and will be tested to their full rating (1700 kVA minimum).

The project has been split into two phases. The Phase I effort, which administratively concluded in February 2002, developed a prototype of a single-phase, full-bridge megawatt inverter based upon newly available HV-IGBTs and combined these newly developed topologies with optical sensing, interfacing, and control. Design parameters concerning maximum voltages, currents, harmonics, and switching frequencies were developed and implemented, in conjunction with the latest developments in optically-based sensors and interconnects.

The Phase II effort, which officially started in May 2002, is currently focused on developing a three-phase version of the Phase I inverter system, and delivering the three-phase system to American Electric Power for testing and certification for grid-connect operations.

Significant progress was made during the fourth quarter of FY03 in the development of the inverter controller, which is based on the Texas Instruments LF2407 digital signal processor, chosen for its chip-integrated inverter control peripherals, an established history for digital motor and inverter control, and low cost. Designed as a modular unit based on the IEEE Std 1101.1 Card Rack Specification, the controller is broken into five separate functional units implemented on a pluggable Eurocard, which allows for system configuration flexibility and ease of maintenance.

## First Quarter Status

Figure 1 shows the main controller installed in one third of the inverter (a phase leg), with missing side panels to facilitate testing and access. The silver cooling fins of the Thermocharge heat pipe system are just visible to the rear of the unit. The system DC storage capacitor is located directly underneath the cooling fins and behind the instrumentation controller.

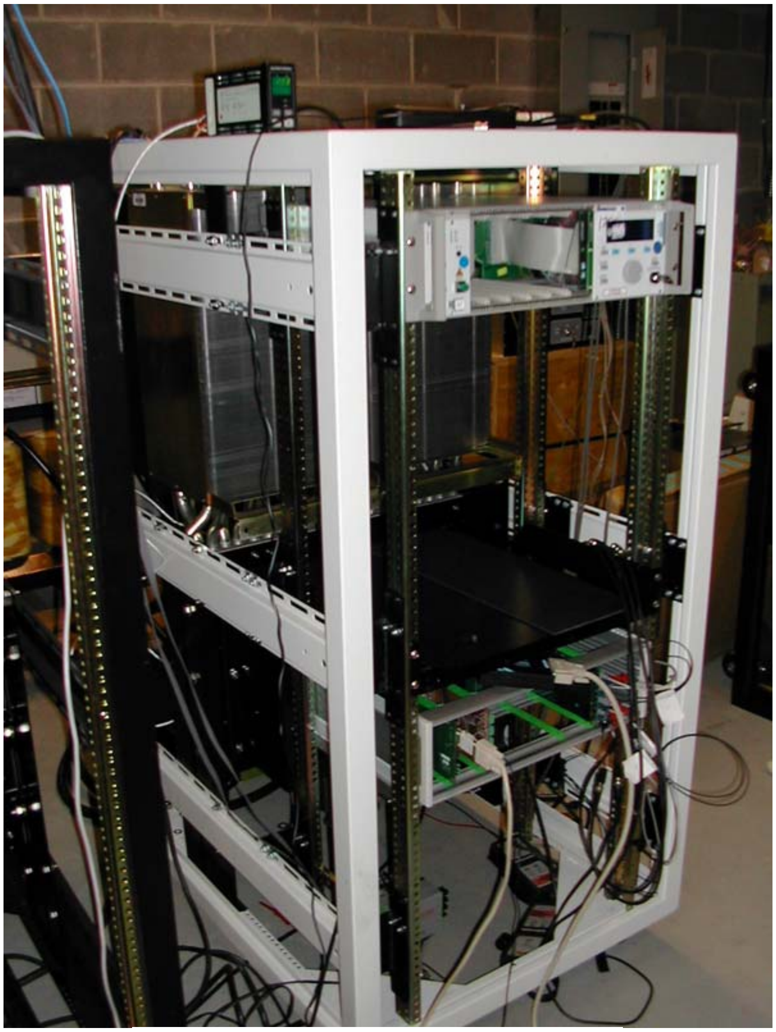


**Figure 1. 1/3rd Phase Leg and System Controller**

Figure 2. shows the system controller card cage. From left to right are the LF2407 DSP PWM controller, the conventional current and voltage sensor interface prototype, and a single-phase optical gate drive controller. The controller card cage, when fully populated, will contain three conventional current and voltage sensor interfaces, two optical sensor interface cards, and three optical gate drive controllers.

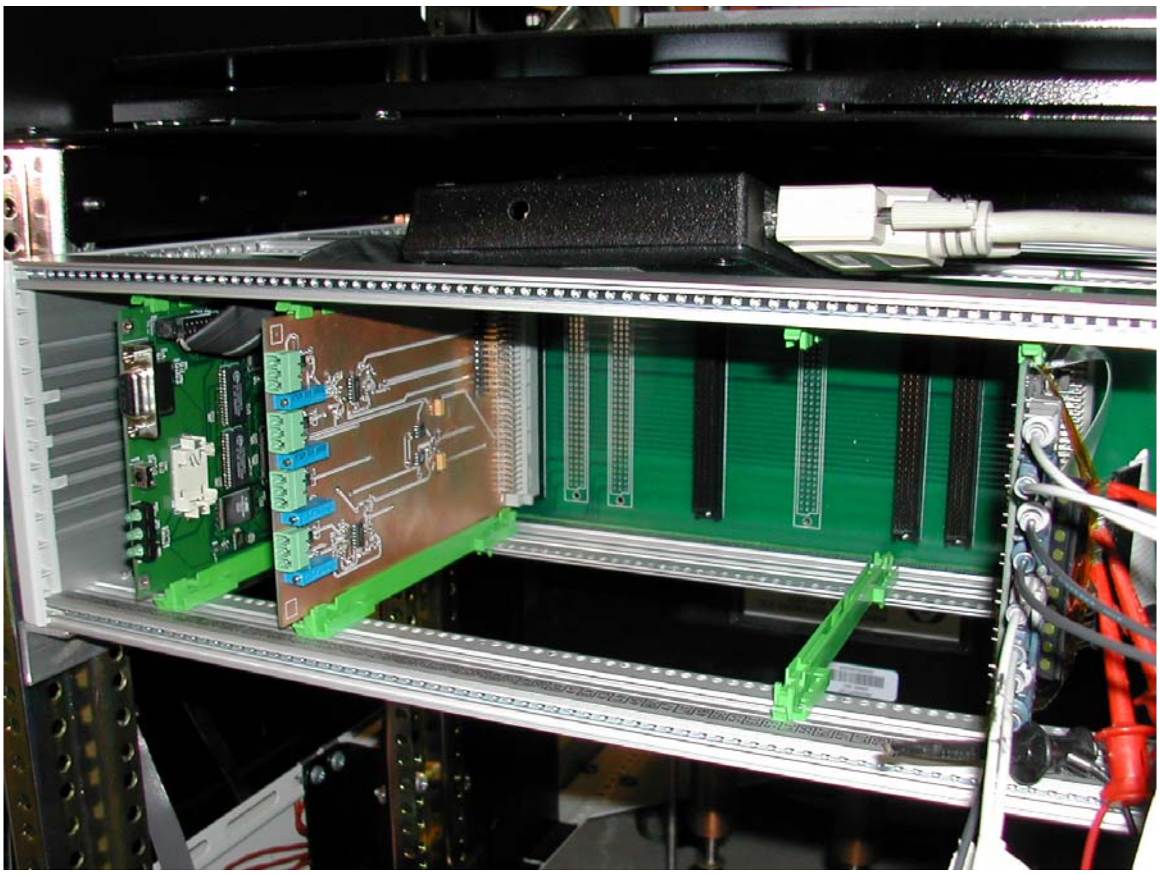


**Figure 2. Inverter controller card cage.**

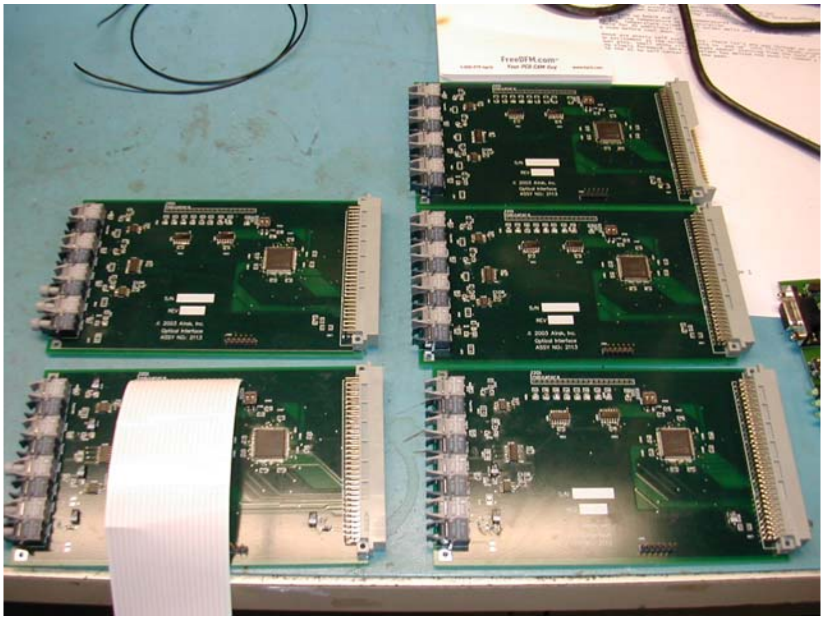


**Figure 3. Fiber optic gate drive interface cards. A total of 6 have been built and tested; 3 are required for system operation.**

The previous gate drive design, shown as the lower board in Figure 4, was a carry-over from boards provided by the Center for Power Electronics at Virginia Tech and was presenting significant problems in the control of the HV-IGBTs at high energy levels. The primary difficulty was attributed to the inability to hold the IGBT in the off state, due to insufficient reverse bias on the gate control. As a result of these findings, a new gate drive board (the upper board in Figure 4) was designed that provides more than sufficient reverse bias, as well as providing additional protection and desaturation circuitry. So far, the boards have performed as expected through 320 kVA. Once a bus bar overshoot issue is cleared, these boards will be tested to full rating (1700 kVA minimum).

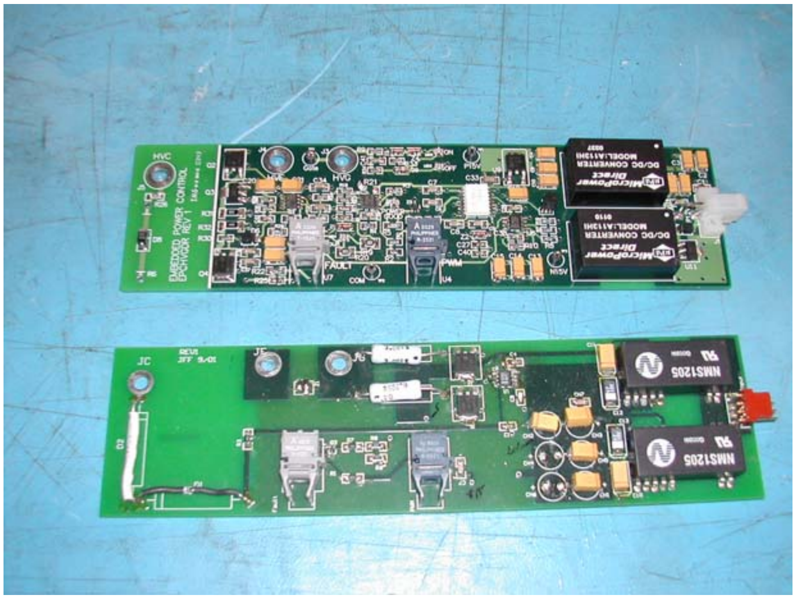


**Figure 9. Old (bottom) and new (top) gate drivers for the HV-IGBTs. The new design provides for improved protection as well as greater reverse gate bias capability.**

In the absence of a final customer for testing and system integration, little more concerning the hardware control of the inverter can be accomplished at this time. Currently, the best candidate for moving this program forward is Beacon Power Corporation with their Smart Energy Matrix program.

Airak and Beacon are working together to identify the best approach at using the system components as developed. Much more work to interface the equipment to a customer's requirements is required, and an estimate of $258K to cover labor, grid-connection and control, and flywheel control integration has been officially submitted to Beacon. Per Beacon Power, the outcome of whether to move forward with Airak's inverter system is dependent upon the California Energy Commission's decision to fund the Smart Energy Matrix demonstration, as well as the level of funding.

During the second quarter of FY04, Airak plans to continue work on the inverter development in the following areas:

- Bus-bar redesign and quoting for manufacture
- Redesign of the DC link capacitor support mechanism.
- Pulse testing up to 320kVA
- Design and construction of a more rugged version of the support for the fiber optic current sensor

Pending identification of a customer, no further work on the inverter is anticipated beyond these four areas.

## ***Low Cost, High Current Advanced Inverter Packaging with Integral Liquid-Cooled Heat Exchanger***

*SNL Contact:* Stan Atcitty
*Contractor:* Rinehart Motion Systems, LLC — Larry Rinehart, Managing Director / Principal Investigator

### Project Overview

This is a new project that began June 21, 2003. The Phase 1 objective of this program is to prove the feasibility of a family of general purpose inverters for DC-AC and AC-DC power conversion that is cost effective from 30 kW to 500 kW. The primary objective during Phase 1 is to design and build a 100 kW proof of concept prototype with improved power cycling life and lower cost. To accomplish this, Rinehart Motion Systems (RMS) established five major goals:

1. Investigate the feasibility of advanced composite materials for an integral pin fin, liquid-cooled, heat exchanger base plate.
2. Investigate design approaches for a double-sided, power hybrid assembly to reduce the footprint, material volume and weight of the base plate.
3. Investigate low inductance inverter and bus structure design alternatives for such a double-sided package, and estimate parasitic inductance.

4. Fabricate several prototype base plate parts and module assemblies to demonstrate feasibility of the approach.
5. Perform temperature or power cycling and vibration testing on the prototype units to demonstrate mechanical integrity and suitability for the automotive environment.

By the start of the first quarter of FY04, RMS had already narrowed the field of candidate materials to three promising alternatives worth pursuing, developed a novel configuration and process for a new non-isotropic composite (AlSiC – Graphite), and developed non-uniform pin composition and pin location techniques to reduce die-to-die temperature differences.

## First Quarter Status

During this quarter, considerable time and engineering effort were expended to complete the modeling and design of a 100 kW inverter with low cost, injection molded materials anywhere high thermal or electrical conductivity is not required. The design is now complete for the inverter heat exchanger and low inductance bus bar structure (see Figure 1).

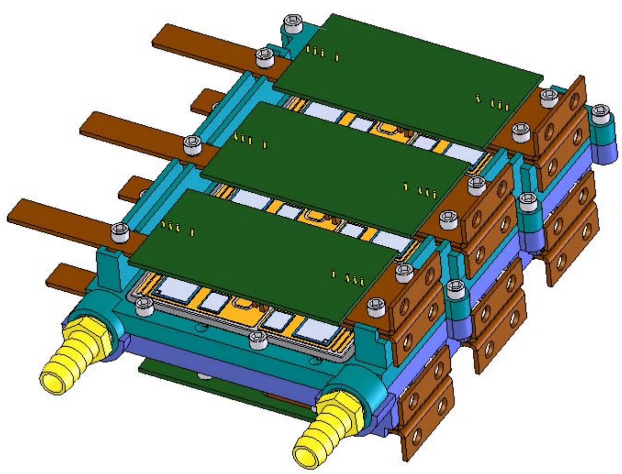


**Figure 1. Water-cooled inverter assembly**.

The project subcontractors for the composite materials have not been able to deliver as quickly as they had originally scheduled, nor have some of the materials matched our expectations. In particular, RMS has eliminated copper-graphite as a candidate material, due to the poor quality of the fabricated sample blanks. The infiltration is not homogeneous, and distinct fracture planes make the machined parts unusable. It is our opinion that this material will not be ready for production in the next three to five years, which is too far out for this program.

The team still holds out great hope for the AlSiC-Graphite and aluminum-diamond materials; but has ordered bases in high purity copper as a backup, to ensure that complete assemblies can be built and tested, even if the exotic materials suppliers cannot deliver.

Now that the detailed design of the heat exchanger is complete, thermal simulations have been repeated on final geometry. At this point, it appears that the 100 kW design target will actually provide 150 kW continuous, and 200 kW peak at a water flow rate of three gallons/minute (GPM). This is excellent news, if it is verified in hardware testing.

In 1993, the US Partnership for a New Generation of Vehicles (PNGV) established metrics and targets for progress in the motor/generator and power electronics assemblies required by hybrid vehicles. This program was replaced with the Freedom Car Initiative in 2002, as part of President Bush's energy strategy; but the targets remain. Compared to the PNGV targets for year 2000 and 2004, the state of the art in industrial and automotive Power Electronics packaging for 50 kW – 100 kW inverter is estimated at:

| | | ***PNGV 2000 Target*** | ***PNGV 2004 Target*** | ***2004 Industrial products (Best of Breed)*** | ***2004 Toyota Prius 2*** | ***New Inverter at 150kVA*** |
|---|---|---|---|---|---|---|
| ***gravimetric*** | *kVA/kg* | *4* | *5* | | | ***15*** |
| ***volumetric*** | *kVA/L* | *10* | *12* | | | ***32*** |
| ***cost*** | *$/kVA* | *$10* | *$7* | *$35* | *$17* | ***$12*** |
| ***efficiency*** | *%* | *95%* | *97 – 98%* | *95%* | *95%* | ***96%*** |

Note – these cost numbers are manufactured cost, not sales price, and include only the inverter power electronics, current sensors, and control. Not included is utility interface hardware, transformers, and switchgear.

It appears that RMS has achieved a calculated cost, weight, and volume advantage.

## FY04Qu2 Plans

First article assemblies built on copper, AlSiC, and AlSiC-G bases and with aluminum nitride and silicon nitride ceramic will be assembled and tested by the end of the second quarter of FY04.

Final bus structure impedance / inductance measurements, bus capacitor temperature rise, power device thermal impedance verification (against the simulated results), and a working inverter running at 480V 60Hz and light load will be completed in early April.

The Phase 1 work effort is scheduled to be completed April 20th, 2004. At this point, there does not appear to be any reason that this deadline cannot be met.

## ***Advanced Lead-Acid Battery Improvement Studies***

SNL Contact: Paul Butler
Contractor: International Lead Zinc Research Organization (ILZRO) — Pat Moseley

**Project Overview**

Continued Research & Development (R&D) on Valve Regulated Lead-Acid (VRLA) battery technology is needed to improve operation, performance, and reliability in the field. This R&D project is a follow-on to the multi-year survey study that was completed in late FY02 on VRLA battery reliability. The study concluded that there are many causes of the reliability problems experienced in the field, and that specific R&D on known areas for technology improvement is well justified.

Such R&D is underway through the Advanced Lead-Acid Battery Consortium (ALABC) organization supported by ILZRO and the lead-acid battery industry. The ALABC has a well-rounded research program focused on key technical areas such as separator development, positive electrode improvement, case seal improvement, and charging optimization studies. The ALABC's total research budget of over $5M (for three-year scope) is heavily leveraged by a modest ESS investment.

The ALABC and its partners have been conducting extensive research that is geared towards improving the performance and enhancing the life of VRLA batteries.

**First Quarter Status**

The ALABC projects that are currently active are:

- Evaluation of different glass microfiber separators and membranes for VRLA batteries working on high-rate partial state of charge (HRPSOC);
- Separator systems for VRLA batteries in HRPSOC duty;
- Development of additives in negative active material to suppress sulfation during HRPSOC operation;
- Optimization of additives to the negative active material for the purpose of extending the life of VRLA batteries in HRPSOC operation;
- Optimization of the negative active material and PSOC cycle life of VRLA batteries for 42-V mild hybrid applications; and
- Influence of trace elements on the performance of VRLA batteries at high temperatures and under HRPSOC.

Due to budget issues, ESS participation in the ALABC is uncertain for FY04.

## ***Super Conducting Flywheel Development***

SNL Contact: Nancy Clark
Contractor: Boeing — Arthur Day

**Project Overview**

This project continues an ongoing design and development effort between the ESS Program and Boeing to mature a new class of flywheel systems with multi-hour storage capabilities. The overall goal of this project is to produce a 3- to 5-kWh flywheel energy storage system for use in a hybrid wind/diesel generation application. This research offers large potential benefits for future large flywheel systems in terms of system efficiency as well as capital and operating costs.

Last year, Boeing worked with the Alaska Energy Authority (AEA) regarding the desired direction for a field demonstration with a wind/diesel hybrid system. After reviewing the data, a 50-kW demonstration system was proposed. A joint Statement of Work for a possible field demonstration to take place in FY04 was drafted and bidding is in process; but funding for the field demonstration has not yet been secured.

The project's goal for FY04 is to build and test the new 'GS' design 5-kWh rim and hub and to initiate design efforts for improving the existing rotor, including improving the rim's axial strength following press fits. The hub and rim for a 5-kWh demonstration system were completed and delivered during FY03. Completion of the hub/rim assembly required three press-fits, two between sections of the rim and one between the hub and the rim (actually a shrink fit). The press and shrink fits were completed and the rim was trimmed to its final dimensions in late FY03.

Because of difficulties in the final assembly of the hub/rim (described below), this rotor will not be used as part of the 5-kWh demonstration system. Rather, work on the new 'GS' design rotor will continue in FY04, with the expectation that a rotor based on the new design will be used in the demonstration system.

Throughout FY03, Penn State University continued its research to expand the knowledge base on fiber composite fatigue strength, including preparation of a paper and a master's thesis on the results of this research. Specifically, a paper on the C-ring method for measuring transverse tensile properties of composites was prepared and submitted to the Journal of Composite Materials. Work for a second, related paper on residual stress effects in these rings was initiated. This materials testing and analysis will continue in FY04.

**First Quarter Status**

The final fabrication step for the hub/rim assembly to be used in the 5-kWh demonstration system was to coat the rim with a clear resin to seal the fibers, which took place early in the quarter. After the coating was completed, a crack was noticed on the inner diameter of the new rotor at a point approximately 0.5 inch away from the hub/rim interface (see Figure 1). The crack was quite obvious; but had not been observed prior to coating.

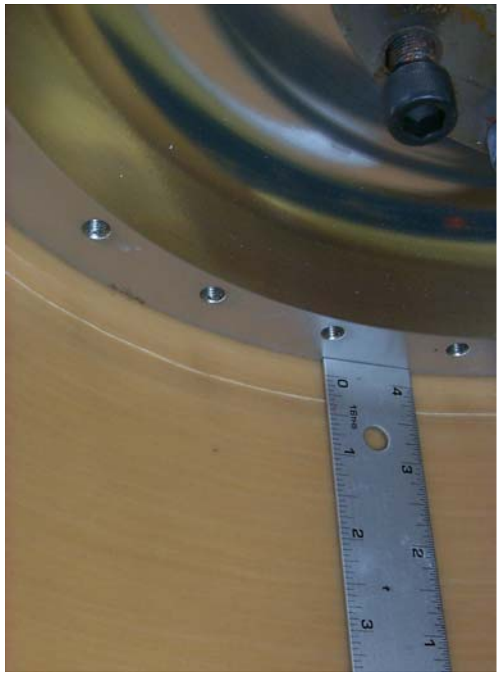


**Figure 1. Interior view of 5-kWh rotor, showing circumferential crack near the hub.**

The crack occurred at a point known to have high residual stresses, but did not extend all the way through the rotor. It was later determined that, although the rotor design was adequate for the anticipated axial stresses at the area of the crack, the strength of the composite materials, specifically the resin used for the clear coat, is reduced at higher temperatures.

The rotor manufacturer investigated the possibility of using a patch ring over the damaged area. It appeared that the patch would reduce the stresses (see Figure 2), although some assumptions had to be made about the depth of the crack. Because the original rim was designed such that the most severe stresses occur when at rest (due to press fits) rather than when spun, it was thought that there was a reasonable probability that the rotor could be repaired and tested. However, given the intention to field this rotor at a remote demonstration site, it was decided not to attempt to repair the rim.

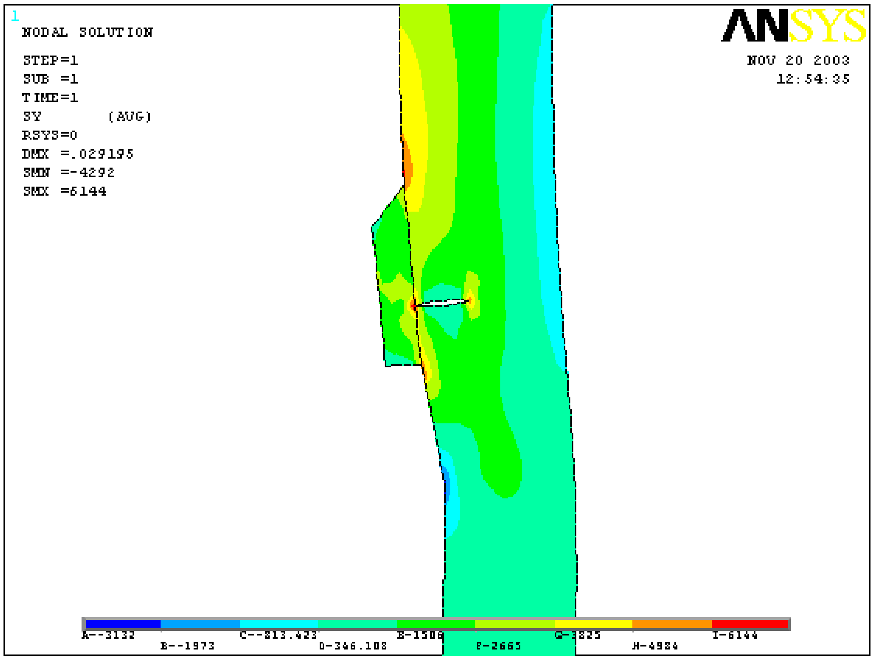



**Figure 2. Axial stress near the proposed repair region at 24,000 rpm.**

Materials testing and analysis continued, with efforts focused on determining the residual stresses in C-ring-shaped test sections. The residual stresses appear to be small, but worthy of some investigation, given the low strength of filament wound materials in the radial direction. Beam-shaped (rectangular) specimens of four different types of carbon/epoxy rings that are used for flywheel rotors were used in flexure tests to evaluate the radial tensile strength and modulus of the composite materials. These results will be compared with the strengths obtained by testing C-ring-shaped specimens.

To promote the materials testing and analysis efforts, work continued on the journal paper “C-Shape Specimen for Tensile Radial Strength of Thick, Polar-Orthotropic Rings.” An abstract was submitted for the paper “Effect of Temperature, Width, and Fiber Angle on Tensile Behavior of a Fiber-Dominated Carbon/Epoxy Composite,” to be presented at the 49th International SAMPE Symposium and Exhibition in May 2004.

## ***Trinity Project – Rotor Materials Tests for Flywheels***

(Formerly: Trinity Flywheel Development)

SNL Contact: Nancy Clark
Contractor: Trinity — Melissa Reading

### Project Overview

The ultimate goal for this technology is to develop a large flywheel system capable of storing 2kWh of useful energy; and the immediate goal is to scale up an existing flywheel system from 100 kW of storagefor 15 seconds to 240 kW for 30 seconds. The project represents the first task in a proposed three-part scale-up effort proposed by AFS Trinity (a flywheel development company) and is part of a cooperative effort between the ESS, AFS Trinity, and the California Energy Commission.

Initial model flywheel systems indicated that the materials used in the smaller system could not be used in larger systems. Work on this part of the project includes building the smaller flywheel system using new fiber, new matrix material, and a new manufacturing process. Once built, this smaller system will be burst-tested to determine the viability of using the new materials and manufacturing process to produce a larger system. The ultimate goal for this technology is to develop a large flywheel system capable of storing 2 kWh of useful energy.

Early in FY03, problems were encountered while manufacturing rotors made from the new materials. It was determined that these rotors could not be mass produced using the rotor supplier's existing manufacturing processes. It was later determined that the rotor supplier would only able to reliably provide rotors one-inch thick or less. Consequently, a new rotor was designed that made use of existing outer rims but with two smaller rims (an 'intermediate' and an 'inner' rim) press fit together to form a new inner rim.

Also last year, four complete rotors were successfully hand built using the new design. Two of them were burst tested with reasonable success late in the year. One of the two rotors developed a hairline delamination crack during the testing which resulted in the suspension of further testing on that unit. The third rotor was burst tested this quarter. The fourth rotor was delivered and will be used to test a flywheel power system under a program funded by the U.S. Department of Transportation.

### First Quarter Status

The fifth (and final) rotor was delivered.

Burst testing of the new rotor design at elevated temperature was an essential first step for any future scale-up efforts. The test concluded with a loss of material from the surface of the rotor which was captured with a variety of diagnostics, including video.

Upon analysis, the rotor was found to have lost a thickness of material approximately equal to one fiber ply along about 90% of the length of the rotor (see Figure 1). The upper and lower surfaces and the corners of the rotor were intact and in good condition. Fiber debris was found on the IR probe on some of the leads, and on the wall of the oven enclosure (see Figure 2). No cracking of the rotor was evident.

**Figure 1. Rotor after test, showing region of lost material.**

**Figure 1. Interior of heated enclosure showing fiber lost from rotor**

All three of the tested rotors were assembled according to standard AFS Trinity equipment and procedures. The first two rotors were tested at the rim manufacturer's facility, and the third at Test Devices, Inc., who built the 'spin pit' used to test the first two rotors. As described in this and previous reports, each rotor experienced some sort of irreversible physical degradation during testing; but none experienced the highly energetic burst typically seen when a flywheel fails a burst test. A report describing the complete results of the burst testing on all three rotors was delivered to SNL.

## ***Advanced Hybrid Controller and DGNode Follow-on Effort***

SNL Contact: Garth Corey
Contractor: Intergrid Consulting — Rob Wills

### Project Overview

Following the bankruptcy of AEI, much of the work on the AHC controller and DGNode was left unfinished. Completion of this work would lead to a completed and fully operational and documented AHC and DGNode. The original PI on the AES contract has the capability to complete the work still required on these items. All other follow-on work originally planned for the next phase with AEI has been abandoned at this time.

Therefore, a contract was placed with Intergrid Consulting (IC) to complete the commissioning of the AHC off-grid hybrid system at the DETL. Other deliverables, such as operating and maintenance manuals, were also included in the IC contract, with delivery still pending.

During the third quarter of FY03, the off-grid hybrid system and AHC were brought to operational status and data was collected. No further deliverables were forthcoming from the contractor.

As of the end of the fourth quarter of FY03, the contractor had not completed all deliverables as required under the contract. The contract ended on September 30, 2003 with less than 50% of the deliverables received.

### First Quarter Status

Under the terms of the contract, the final deliverable of a fully operational and documented micro-grid simulator must be complete in order to qualify for final payment.

During the first quarter, the contractor invoiced for the full amount of the contract and the project manager rejected the invoice because all terms of the contract had not been met. The contractor was notified that he must complete all tasks before the invoice will be paid. Therefore, funds for the total amount of the contract were carried over into FY04.

This project is being discontinued.

## ***Super Capacitor Testing***

SNL Contact: Tom Hund / Nancy Clark
Contractor SNL — In-house project

**Project Overview**

EPRI PEAC is building an energy storage system for power quality and transmission line stability using ultracapacitors. Sandia National Laboratories (Sandia) is supporting this work by conducting laboratory testing on the Russian-made ESMA EC502 and Japanese-made ECaSS® PMLF 54-65 ultracapacitors, which has a projected cycle-life of 100,000+ cycles and a very short recharge time.

The high charge and discharge rates and long cycle-life of these ultra-capacitors could make them an ideal replacement for batteries in power quality, transmission line stability, and hybrid electric vehicle applications that require high power for short time durations without the need for frequent replacements due to a low cycle-life.

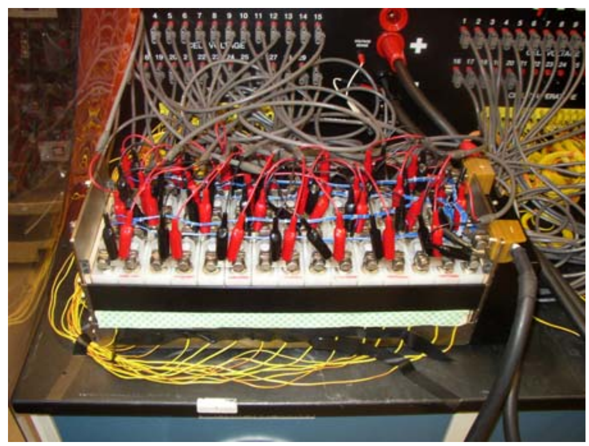


**Fig. 1: ESMA EC502 Ultracapacitor**

In figure 1 is the ESMA ultracapacitor. It is an electrochemical capacitor consisting of a negative electrode made of activated carbon and a positive electrode made of nickel hydroxide. This capacitor design has a greater specific energy and discharge rate compared to capacitors with two carbon electrodes. Their cycle-life is projected to be 100,000+ cycles, with a recharge time of only a few minutes, or less. In figure 2 is the ECaSS® ultracapacitor, consisting of a symmetric electrochemical non-aqueous carbon-carbon design. This design uses activated carbon on both electrodes and the nonaqueous electrolyte allows for a cell voltage of 2.7 volts vs. the 1.5 volt cell used in the aqueous ESMA ultracapacitor.

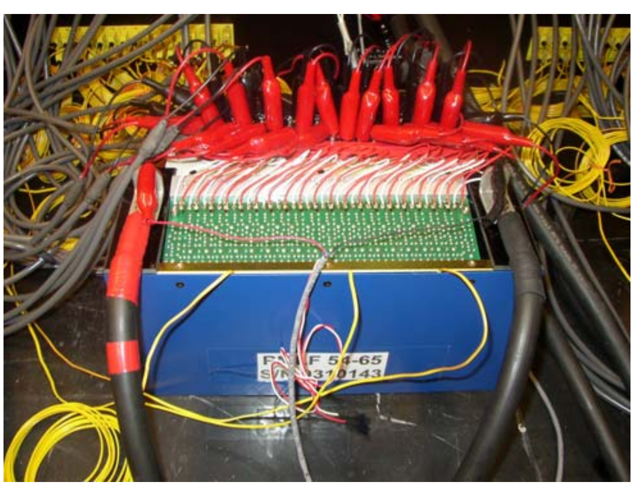


***Fig 2: ECaSS® PMLF 54-65 Ultracapacitor***

A key factor in the success of the ultra-capacitor technology is its ability to maintain stable cell voltages within the capacitor cell string. Excessively low cell voltages can result in cell voltage reversals, causing excessive heating or cell damage. To prevent this condition, both ESMA and ECaSS® have built into their ultra-capacitor module a cell voltage leveling-circuit. The leveling circuits should charge low voltage cells to prevent cell damage.

**First Quarter Status**

A new test plan was prepared, and approved by all, that included a cell capacity test, a cell impedance test, a cell leakage current test, a cell self-discharge test, and a module cycling and float test.

During this quarter, testing was initiated to evaluate the ESMA and ECaSS® ultra-capacitor performance. The initial module test results indicate that there is still a need for improved cell-leveling. Over time, unbalanced cells would degrade performance and cycle-life. This testing sequence should be completed in the second quarter of FY04.

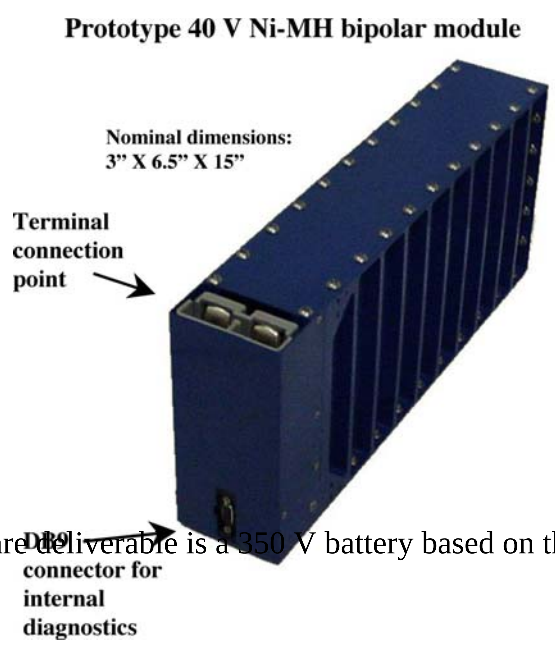
## ***Nickel Metal Hydride Bipolar Battery Development***

*SNL Contact:* David Ingersoll / Nancy Clark
*Contractor:* Electro Energy, Inc. (EEI) – Mike Eskra

**Project Overview**

This is a direct, congressionally funded project that began late in the fourth quarter of FY2002. Electro Energy, Inc. (EEI) has undertaken development of a bipolar nickel metal hydride battery whose performance characteristics could meet a variety of energy storage application needs, including high voltage/high power modules with high cycle life. In FY03, the deliverable for the first year of the program was a prototype cell and a battery module, the latter meeting nominal capacity, voltage and power requirements of 6 Ah, 40 V, and greater than 10 kW, respectively. FY04 plans call for a 350 V battery based on the cell and module designs developed in FY03.

The image below depicts the device that was delivered during FY03.




For FY04, the hardware deliverable is a 350 V battery based on the cell and module designs developed in FY03.

## First Quarter Status

In the first quarter of FY04, we continued electrical evaluation of the prototype module that was delivered to Sandia, and the initial testing was an evaluation of its behavior under high power conditions. The device performed as expected, and was easily able to support repeated 10-second pulse power loads of approximately 4 kW each. Evaluation of this module is continuing.

The 350 V battery being developed for FY04 activity was fabricated and is currently undergoing preliminary electrical evaluation at Electro Energy, Inc. A photograph of this battery is shown below.


**Prototype 350 V Nickel/metal hydride bipolar battery.**

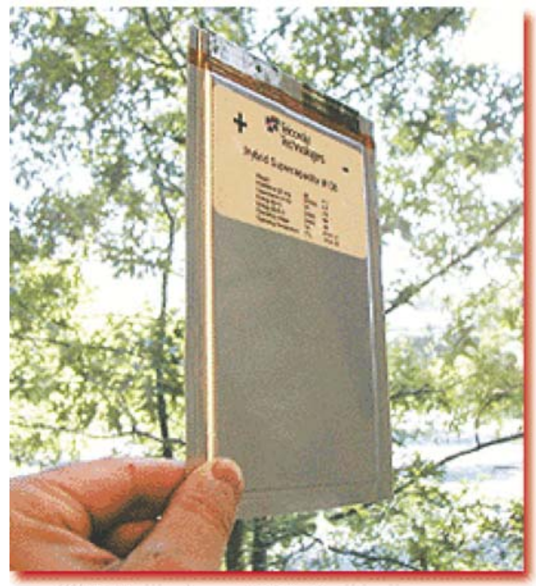
Negotiations for third year activities have commenced, and are expected to be concluded during the second quarter of this year.

## ***NanoMaterial-Based Electrodes for Energy Storage Devices***

*SNL Contact:* David Ingersoll / Nancy Clark
*Contractor*: NEI Corporation (formerly Nanopowder Enterprises, Inc.) – Dr. Amit Singhal

**Project Overview**

A new area of materials research and development is centered on the preparation of nano-sized materials. This SBIR activity focuses on new materials development and delivery of a prototype of nano-material-based electrodes for energy storage systems. NEI Corporation is one of the companies that are involved in this new area of materials development, and they have identified candidate nano-materials that could significantly improve the performance characteristics of energy storage systems that utilize these materials. One of those materials is tungsten-oxide ($WO_2$), which loses only 10% of its rate capability and maintains good cycle life after doubling the current from 22.5 mA/g to 45 mA/g.

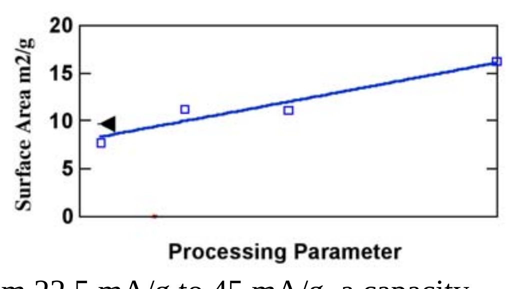


Cell Dimensions: 6” X 4”
(Courtesy Telcordia Technologies)

Toward this end, NEI has embarked on a program designed to prepare and evaluate the behavior of candidate nano-materials, such as $WO_2$, that will be used to fabricate a prototype, asymmetric hybrid cell. Sandia National Laboratories (Sandia) is evaluating the laboratory prototype depicted in the picture above.

**First Quarter Status**

NEI is continuing the development and evaluation of novel nano-materials, and they have developed methods for controlling the surface area and crystallite size of nanostructured $WO_2$. The data shown in the figure at the right provides an example of the control that can be obtained through control of the processing parameters.




NEI has also demonstrated that nano-structured $WO_2$ electrodes exhibit good rate capability. In this case, they have determined that, upon doubling the current from 22.5 mA/g to 45 mA/g, a capacity loss of only 10% is observed while still maintaining good cycle life. Furthermore, the capacity of the nanostructured material is higher than that observed with the standard sized materials. In the case of nanostructured $WO_{2,}$ the first cycle discharge capacity is 572 mAh/g, as opposed to only 328 mAh/g for standard-sized materials. In both cases, these values are significantly higher than the theoretical capacity of approximately 120 mAh/g, which suggests that a second charge storage mechanism is operating in addition to the conventional lithium intercalation process.

*Ex-situ* X-ray diffraction measurements on electrodes of nanostructured $WO_2$ during the first delithiation and lithiation steps have been made in order to attempt to understand the secondary charge storage processes. It was found that the nanostructured $WO_2$ particles transform to an amorphous phase on lithiation (charge); and on delithiation (discharge), the amorphous phase reverts to the nanocrystalline $WO_2$ phase. It can be inferred from these data that the reduction of nanostructured $WO_2$ with Li is reversible and is responsible for the higher first discharge and charge capacity.

# STRATEGIC ANALYSIS

## *PCS Magnetic and Functionality Analysis*

*SNL Contact:* Stan Atcitty
*Contractor:* New Mexico State University (NMSU) — Dr. Satish Ranade

**Project Overview**

During FY00 and FY01, Dr. Ranade, on a consulting basis, provided requested information, resources, and technical insights for interfacing electrical utility systems with energy storage systems. His deliverables were white papers on topics requested by SNL**.**

In FY02, Dr. Ranade focused on issues related to Distributed Energy Resources (DER) and associated Power Conversion Systems (PCS). Two specific topics addressed were the effect of motor starting on the operation of isolated DER and the modeling of DERs in electric distribution systems.

Typically, under isolated conditions, a DER cannot start moderately large motors because the PCS cannot supply the starting current required. Therefore, Dr. Ranade's purpose was to examine the use of capacitive energy storage to assist in motor starting. A scheme based on electro-chemical capacitors and a simple PCS was developed and simulation studies suggest that the scheme can effectively assist the DER with transient loads. The scheme has now been implemented under a separate project as proof-of-concept.

FY03 work focused on a different application of capacitors; specifically, the use of polarized, electrolytic capacitors in ac applications.

**First Quarter Status**

No activities performed by the contractor during First Quarter. This project will be terminated, due to lack of DOE funding.

## ***Short vs. Long-Term Energy Storage Technologies Assessment***

*SNL Contact:* Paul Butler
*Contractor:* 122 West — Susan Schoenung

### Project Overview

This assessment is a continuation of the study performed in FY99 (SAND2000-1550) that identified technology opportunities for both short and long duration applications of energy storage. Based on the first study, the comparison of storage technologies with alternative options on a life-cycle cost basis was identified as needing further analysis. While first-cost considerations will commonly favor generation, life-cycle costs, including the impacts of environmental effects, might favor storage. A final report on this work was published in August 2003.

At the end of FY03, work began on a continuation of this study and focused on life-cycle cost algorithms and the establishment of a list of parameters for a sensitivity analysis. This analysis will quantify the tradeoffs and comparisons using internal combustion generators fueled by a variety of sources, including natural gas, hydrogen, and diesel. This work phase will include the following tasks:

Task 1. Additional Application and Technologies for the Life Cycle Cost Study

Task 2. Sensitivity Studies

Task 3. Energy Storage Systems Site Analysis Approach

Task 4. Energy Storage Systems Cost Parameters Workshop

More detailed analyses and sensitivity calculations of the various technologies for the utility applications of storage defined in the Opportunities Analysis Phase 2 study are to be performed. The characteristics to be evaluated include energy density, power density, and duration of discharge and charge.

### First Quarter Status

Work on the sensitivity analysis has been completed. The sensitivity results on expected life are quite useful. When shortening the life expectancy from 20 years to 10 years, for example, the annual capital cost component goes up (because the payback rate is higher); but the replacement costs decrease in some cases. The results of the 1-hr and 4-hr distributed generation cases are shown in Figures 1 and 2, respectively.

Work has been initiated on Tasks 1, 3, and 4 with regard to approach and actions required. Actual analysis has been put on hold pending resolution of the ESS Program budget in FY04.

Plans for the next quarter include continuing work on Tasks 1 and/or 3, or beginning work on the Workshop; but discussion with Sandia personnel is needed to plan future activities, depending on available resources.

## ***Value of Storage for Restructured Utilities***

*SNL Contact:* John Boyes/Paul Butler
*Contractor:* DUA — Joe Iannucci

**Project Overview**

This project is a continuation of a study initiated in 1998 (SAND2000-1550) that defined several possible electricity-provider scenarios for the use of energy storage following the restructuring of the U.S. electric utility industry. Some combination of the Power Cost Volatility and the T&D Benefits SMOs would be the most compelling for further investigation. F rom 2001 to 2010, a combination of benefits (energy, capacity, power quality and reliability enhancement) achievable using energy storage systems for high value T&D applications, in regions with high power cost volatility, makes storage very competitive for about 24 GW and 120 GWh.

In FY00-01 (Phase II, SAND2003-0362), five of the most promising scenarios were selected as having the highest potential to make a substantial impact on the electricity delivery system. During FY02-FY03 (Phase III), the economic benefits of energy storage were evaluated for a combined application involving arbitrage (buy-low, sell-high) plus T&D deferral.

In addition to estimating the various financial expenditures and the value of electricity that could be realized in the marketplace, technical characteristics required for grid-connected distributed energy storage (DS) used for generation capacity deferral were also explored**.**

A draft of the Phase III report, titled "*Innovative Applications of Energy Storage In a Restructured Electricity Marketplace Phase III Final Report*" is in final review. A statement of work for a Phase IV study was drafted and a contract amendment negotiated with DUA.

**First Quarter Status**

The DOE/ESS Program budget for FY04 has yet to be resolved and, until it is, only modest work will be performed on this project.

An updated summary on current activities will be presented in the FY04 second quarter report.

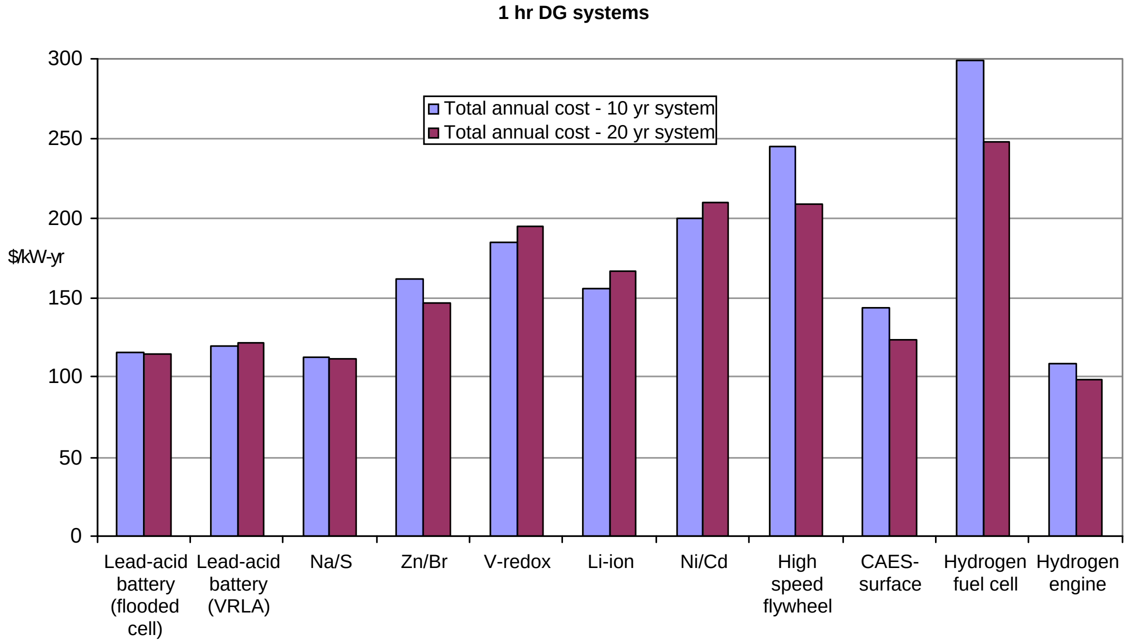



**Figure 1. Sensitivity of total annual cost to expected life of 1-hr Distributed Generation systems**

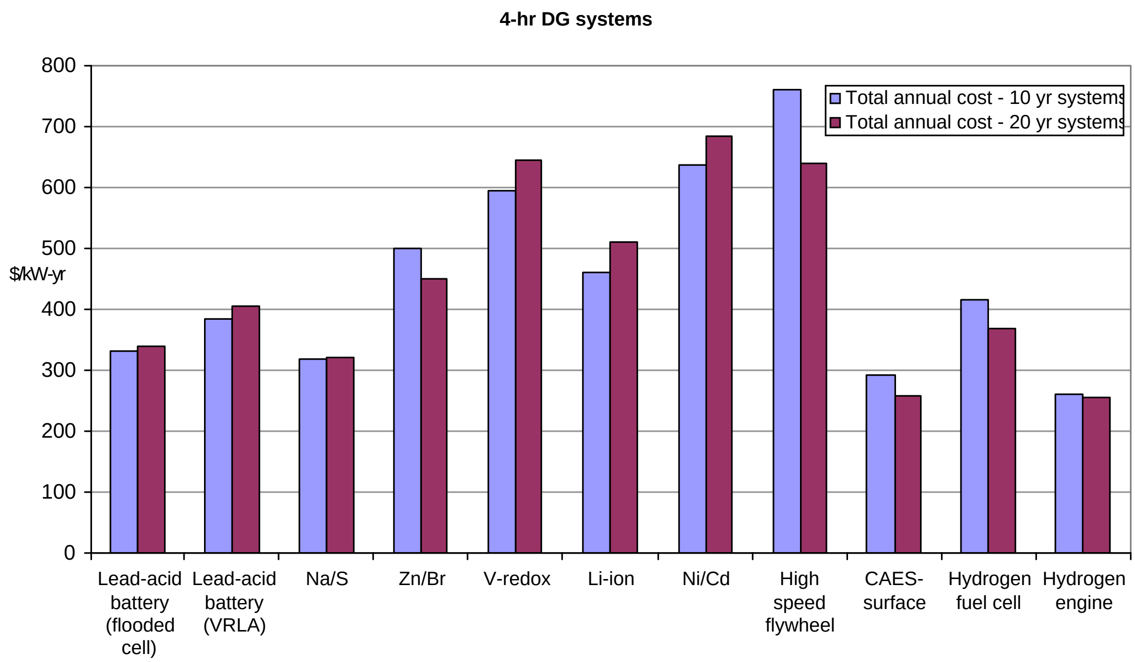



**Figure 2. Sensitivity of total annual cost to expected life of 4-hr Distributed Generation systems**

## ***EESAT2003 (Electric Energy Storage Applications and Technologies Conference)***

*SNL Contact*: Georgianne Peek

### Project Overview

EESAT2003 was conducted October 27-29, 2003, at the Sir Francis Drake Hotel in San Francisco, CA.

Sponsored by the DOE ESS Program and and attended by 151 participants from 13 countries, EESAT03 presented a wide range of electrical energy technologies, including conventional and advanced battery energy storage, super capacitors, SMES, flywheels, CAES and pumped hydro, with an emphasis on the latest commercial developments for the use of electricity storage in the power industry.

EESAT2005 will again be held at the Sir Francis Drake, October 17-19, 2005.

### First Quarter Status

Negotiations with the Drake Hotel for EESAT05 are in process.

## ***Economic Evaluation Support for CEC/DOE Energy Storage Initiative***

*SNL Contact:* Garth Corey
*Contractor:* Distributed Utility Associates (DUA) — Joe Iannucci

### Project Overview

The purpose of this contract is to obtain, analyze and disseminate data on energy storage system economics and realized benefits for all CEC/DOE Energy Storage Initiative Demonstration Projects currently scheduled for commissioning in the State of California during CY2004 and CY2005 under sponsorship of the CEC and DOE.

The Economic Evaluation Data Management contractor (EEDM) is responsible for conducting analyses of the storage system economic performance for each of the energy storage demonstrations. The EEDM is also responsible for the verification and validation of source data used for all economic analysis activities for each of the energy storage demonstrations.

### First Quarter Status

On December 22, 2003, a four-year contract was placed with Distributed Utility Associates to specifically access the economics of each of the projects in the CEC/DOE Energy Storage Initiative. Because of the delay in placing the contract, no progress is reported for the first quarter.

Early in the second quarter, DUA will review the proposed economics for the three projects that are to be funded under the initiative. For the first deliverable under the contract, DUA will develop a document that will show the CEC contractors how the economic benefits will be evaluated during the project. The document will be distributed to the CEC Project Contractors at the project kick-off meeting.

## ***United States Coast Guard, National Distress System, Electric Power System Optimization Study***

*SNL Contact:* Garth Corey
*Contractor:* SNL In-house project
*Partner:* US Coast Guard — LCDR Romualdo Domingo

**Project Overview**

Sandia is working closely with the US Coast Guard (USCG) to assist that agency in improving battery systems management in the electric power systems currently in use at remote sites in the National Distress System (NDS). Recent developments at Sandia in the optimization of system management techniques utilizing 10 kW class ACONF (alternative configuration) in parallel battery strings have the potential to significantly improve battery performance and life expectancy for batteries used in the NDS power systems.

This is the first Department of Homeland Security WFO (Work For Others) effort to be managed by Sandia National Laboratories (Sandia). The project originated during the second quarter of FY03 as a Sandia WFO "funds-in" program that is being cost-shared by the DOE/ESS Program.

The USCG accepted a proposal from Sandia's Distributed Energy Test Laboratory (DETL) to study and evaluate the expected increase in performance of the NDS power system. This study compares the performance results of two identical NDS power systems, one operated in its original configuration and the second operated under the control of an advanced battery management system developed by Sandia. The cost-share portion of this project for the DOE ESS Program is the management and operational analysis of the two systems.

Final design of the facility to be installed at the DETL was completed during the third quarter of FY03 and the DETL ordered all hardware needed for the project. The batteries were delivered during that time, and final preparation and wiring of the NDS test set-up were completed. Primary components of the data acquisition system were installed and readied for calibration awaiting final installation of the gensets (generator sets). The propane handling system, which cleared all ES&H reviews, was installed and prepared for hook-up to the gensets.

Problems occurred with the delivery of the propane generators from Mechron, a Canadian manufacturer, as the proper customs paperwork did not accompany the generators and Customs impounded the units while the proper paperwork was prepared.

**First Quarter Status**

The Mechron propane generators cleared customs in the first quarter of FY04. They were installed and put into operation soon after their delivery to the DETL. The ACONF test unit was delivered and installed in early October. All installation work was completed prior to the end of the first quarter. Preliminary battery capacity testing was completed during the first quarter with the batteries exhibiting nominal performance as expected. Other characterization testing was also completed in the first quarter in final preparation for commissioning.

System commissioning was delayed and rescheduled for the second quarter FY04.

## ***VRLA Battery Life Study***

*SNL Contacts:* Rudy Jungst, Angel Urbina
*Contractor:* High Power Research Laboratory (HPRL) – Bor Yann Liaw

**Project Overview**

Valve-regulated lead-acid (VRLA) battery life prediction continues to be problematical and its failure modes are not well understood, particularly by the user community. The inability to predict battery failures has led to a situation in back up power applications wherein costly inspections and performance monitoring must be performed frequently to verify system readiness in case a utility power outage occurs. This situation is especially troublesome given that one of the expected benefits of a VRLA battery system is reduced maintenance cost.

The goal of this study is to develop a model of VRLA battery life for use in float applications. The model could be used to predict battery failures so that maintenance and replacements could be furnished in a timely manner. The intent is to be able to anticipate cell failures far enough in advance that replacements can be put in place before battery down time is actually incurred.

In this study, appropriately, measurable battery characteristics are being selected and related to float life through advanced mathematical modeling. In addition, fuzzy logic techniques are being applied to determine the relationship of battery use profiles, battery characteristics, and battery failure mode patterns to float life.

The general approach is to first survey existing battery life data and augment it with additional test data, as needed. Inductive models, such as artificial neural networks (ANNs), are then constructed using the battery properties that are most strongly correlated with float life. The models are adaptive and can, therefore, be easily refined as more data become available or as additional field experience is accumulated.

Initial work focused on developing a practical capability to model VRLA battery performance and degradation. A review of recent literature revealed that an equivalent-circuit diagram-based approach might be promising; although, it would need to be extended to include other important aspects of battery behavior. For battery float life prediction, these aspects would include self-discharge, charging efficiency, transport properties, and degradation processes.

SNL has focused on the ANN model, while HPRL focused on the ECM (Equivalent-Circuit Model) simulation development.

Develop Battery Performance Simulation Model using an Equivalent-Circuit (EC)-Based Approach.

The ECM work included the adoption of a unique feature that separated the ohmic resistance components and faradaic non-linear components into different circuit elements. This model was favored due to its simplicity in describing behavior of an electrochemical system and the success enjoyed in modeling a variety of chemistries, including VRLA.

Due to the lack of suitable data for VRLA, we used data that were available to us via the DOE Advanced Technology Development program for lithium-ion batteries (LiB) to develop the modeling capability and conduct a feasibility study. Although we showed that we could estimate cell capacity fade as a function of impedance changes measured in the higher SOC range above 60%, the result did not accurately predict capacity fade as determined by reference performance tests (RPTs).

A more detailed analysis of the capacity behavior of the aforementioned set of test cells was carried out to dissect the contributions of the various resistance components in the model. The resistance changes induced by thermal aging are most rapid in the lower SOC regime. Further analysis of the resistance changes and the impacts on the discharge behavior will be necessary to adequately simulate their effect on the capacity fade.

Develop Battery Performance Simulation Model using a Neural Network Modeling Approach.

The equivalent circuit model (ECM) provided by Dr. Liaw and Sandia was used to generate surrogate data in the absence of experimental data. This data was used to demonstrate that a recurrent neural network can provide reasonable predictions of the battery discharge capacity over cycles. A particular type of neural network known as the connectionist normalized local spline (CNLS) was implemented and used in the study. The modeling process involved constructing a neural network as a metamodel to enrich the original data set generated by the ECM. It was also demonstrated that a recurrent neural network coupled with genetic algorithm adaptation could improve the prediction.

A principal components-based uncertainty modeling and quantification technique was used to assess the predictive accuracy of the recurrent neural network. The uncertainty bands estimated by the model successfully captured the discrepancy between the neural network-predicted and metamodel-generated cycle histories, which demonstrated the uncertainty model's ability to assess predictive accuracy.

**First Quarter Status**

Presentations on the preliminary results from the ECM and ANN model development were given at the EESAT 2003 meeting and at the Electrochemical Society meeting in the fall of 2003. Further refinement of both models will be necessary to obtain the high level of accuracy desired for battery life prediction.

The lack of data on VRLA battery tests also continued to hamper the modeling work. A data set on VRLA battery performance was received from GNB near the end of FY03 and key results must be extracted in order to begin detailed simulation studies on that system.

This work was not resumed in the first quarter due to uncertainty regarding FY04 funding.